Bulletin
of
The Geological Society of America

VOLUME 68 June 1957 NUMBER 6

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Subscription $15.00 per year.
Printing Office: Mt. Royal & Guilford Aves., Baltimore 2, Md.
Communications for publications should be addressed to The Geological Society of America, Dr. H. R. Aldrich, Secretary, 419 West 117 Street, New York, N. Y.
Please give notice of change of address 4 weeks in advance. Claims for nonreceipt of the Bulletin of a given month must be sent to the Secretary of the Society before the end of the second succeeding month.

Entered as second-class matter at the Post Office at Baltimore, Md., under the Act of Congress of July, 16, 1894.
Accepted for mailing at special rate of postage provided for in Section 1103 Act of October 3, 1917, authorized on July 8, 1918.

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BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 68, PP. 657–674, 4 FIGS., 3 PLS. JUNE 1957

TACONIC KLIPPE: A STRATIGRAPHIC-STRUCTURAL PROBLEM

BY WALTER H. BUCHER

ABSTRACT

The concept of a klippe was applied to the Taconic region of the Hudson River valley to explain the occurrence, side by side, of contrasting facies of supposedly time-equivalent rock formations: the autochthonous carbonate sequence, and the clastic Taconic sequences interpreted as allochthonous. For the southern half of the Taconic region the structural evidence is incompatible with the hypothesis. An alternative view, which attempted to see in the two sequences facies deposited essentially *in situ* in one basin does not explain the remarkable uniformity of the carbonate stratigraphy over the whole region.

Field studies by the writer and several of his students have produced results that suggest that some of the stratigraphic units are not time equivalents as had been supposed. Three important unconformities, produced by broad arching and subsequent erosion, separate the following stratigraphic units: (1) The Lower Cambrian clastic series (Poughquag-Stissing in the south, Nassau-Schodack in the north) from the Upper Cambrian to Canadian carbonate series. Locally the latter lies on Lower Cambrian and even on the Precambrian. (2) The carbonate sequence from the Schaghticoke-Deepkill-Lower Normanskill shale sequence, which locally rests directly on the Precambrian or Lower Cambrian. (3) The Schaghticoke-Deepkill-Lower Normanskill series from an Upper Normanskill series (of Middle Trenton age) which transgresses far and wide across all earlier formations on to the Precambrian.

Most of the paper is devoted to specific evidence from over a dozen quadrangles. Twenty-nine critical localities are shown on a key map together with broad geologic features. A few significant structural details are illustrated with drawings and photographs.

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Introduction

The Taconic "klippe" of Early Paleozoic rocks, as drawn on the tectonic map of the United States (Committee on Tectonics, 1944) along the Hudson River in northeastern New York, is more than twice as long, though not as wide, as the prototype of extensive klippen, the Préalpes of Haute Savoie and Fribourg in the western Alps. It is represented as bounded on all sides by a thrust contact which implies that all the rock material within it is foreign fallochthonous) to the native (autochthonous) (ormations around it on which it is thought to lie as an alien body.

Such a striking object, over 150 miles (240 km) long and on the average 10 miles (16 km) wide, should occupy a prominent place in American structural geology. But it does not. While it is mentioned and illustrated in discussions of the tectonics of the Northern Appalachians (Eardley, 1951, p. 150–157; King, 1951, p. 102–106), there exists for it no counterpart to such works as Lugeon's epoch-making monograph on the Préalpes (1902), Jeannet's masterly summary in Heim's "Geologie der Schweiz" (1922, p. 589–676), or Bailey's summary (1935, p. 58–89).

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(2) The concept of klippe was introduced here originally to explain the occurrence, side by side, of contrasting facies, and not for structural reasons at all. In fact, when it was first applied in the central Hudson Valley it was accepted as necessary, though structural evidence was lacking. Even at the northern end of the Taconic belt, where its rocks, rising like typical klippen above the surrounding autochthonous formations, invite the interpretation which may well here apply (Keith, 1933, Pl. 8, opp. p. 51), the dominant argument is still that of contrast in facies (Keith, 1932, p. 399).

Thus the Taconic region which produced a *cause célèbre* in the first half of the last century (Merrill, 1924, p. 594–614), is still a center of debate that stirs imagination and tempers. This is, of course, a sign that essential facts are missing and that intellectual curiosity and zest are in a healthy state.

For the last 12 years, the writer has taken an active interest in the study of Taconic structure. Two major and several minor contributions have resulted from investigations by his students. The former, by John Weaver and J. C. Craddock, are being published together with this paper, in which all the contributions are summarized in a general survey of the problem as the writer sees it at present.

Origin of the Klippe Hypothesis

What Led to the Hypothesis

As drawn on the Tectonic Map of the United States (King *et al.*, 1944), the outline of the "klippe" separates two terranes of contrasting lithologies. Outside of it, the Cambrian and pre-Trentonian Ordovician rocks are largely dolomites and limestones. Inside, the same large time interval is represented by quartzites, sandstones, shales, and radiolarian cherts. Interbedded carbonate layers are present only locally and in negligible amounts. The so-called autochthonous carbonate sequence contains practically no argillaceous material up to the end of Chazyan time and so is light-colored. Only the Black River limestones are dark-colored and contain shale partings. The alleged allochthonous terrane, on the other hand, is largely somber-colored, with tints ranging from greenish gray and gray

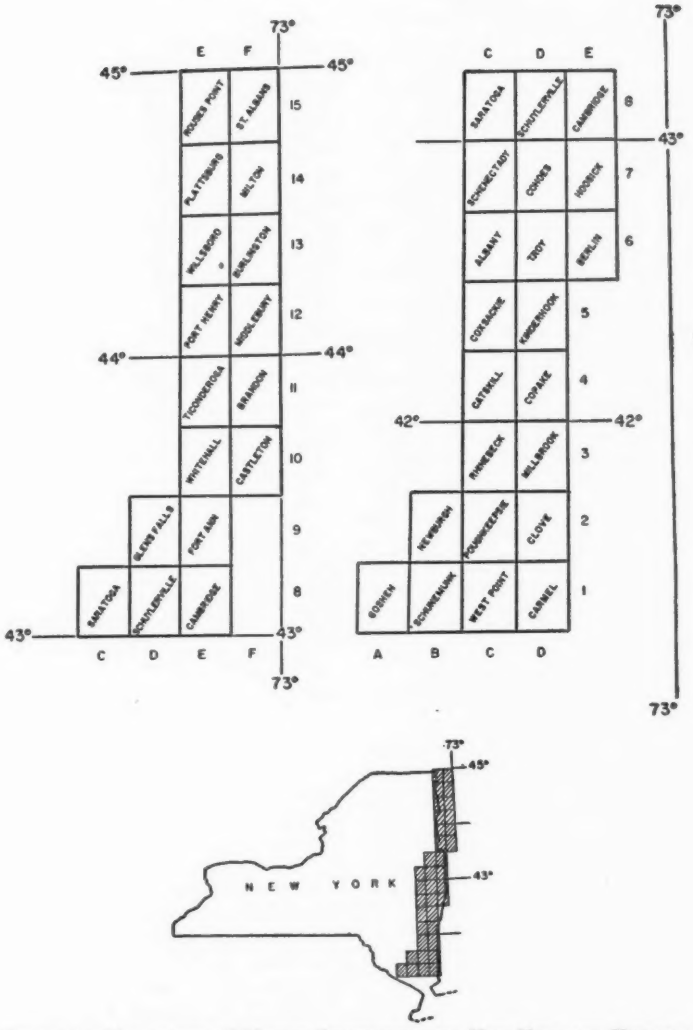

FIGURE 1.—MAP OF THE 15-MINUTE QUADRANGLES IN NEW YORK AND VERMONT

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The contrast between these two terranes is so great, the formational units in each maintain their characteristics over such distances, they lie so close together, and transitional beds are so few, that they could not well have been deposited side by side where they now lie.

This led Ulrich to the hypothesis that these and similar belts to the east and north were "deposits in originally distinct troughs that have since been thrust westward over each other" (Ulrich, 1911, p. 443). Ruedemann applied this generalized idea to the detailed mapping and analysis of the Saratoga-Schuylerville quadrangles (Fig. 1, C8, D8), where he believed he saw "undisputable evidence of at least two parallel troughs in the two entirely different sets of formations described" (Cushing and Ruedemann, 1914, p. 114). He used this concept in mapping the adjacent four quadrangles of the Capital district (Fig. 1, C6, D6, D7, C7)

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What Cast Doubt on the Hypothesis

For 52 miles along the entire master fault which is supposed to mark the western border of the "klippe" on the quadrangles concerned, the Snake Hill shale is shown lying side by side with the Canajoharie shale of the same age, or with the slightly younger Schenectady beds, after an assumed transport of tens of miles. It is unbelievable (1) that the whole western border of the "allochthonous" sequence could consist exclusively of the youngest formation and (2) that this border should lie in contact only with beds of the same or slightly younger age.

Moreover, Ruedemann knew that the existence of a master fault, the "sole of the thrust," could not be proved and that the field evidence was against it. He wrote, "This overthrust plane has nowhere been directly observed, not even in the section along the Mohawk river, where it would be most liable to appear. In its place appear a number of small overthrust planes. It is therefore our conviction that the overthrust is dissolved into a multitude of smaller overthrusts" (Ruedemann, 1930, p. 137). The throw on these is measured in inches rather than feet. Moreover, the intensity of deformation increases gradually eastward across the supposed western edge of the "klippe."

After the writer has seen these and other critical exposures on a 6-weeks' reconnaissance trip in 1942, the hypothesis of the contents of two originally separate sedimentary basins piled one on the other by long-range thrusting seemed to him untenable. It appeared more probable that the formations of the shale sequence are simply the inner facies of the sediments of a single basin where the carbonate sediments formed the marginal facies. In the same year, Reudemann himself (1942a, p. 174–175; 1942b, p. 53–59) proposed this alternative in a decided change of outlook. (*Compare* Ruedemann, 1930, Fig. 8, p. 131, with 1942b, Fig. 9, p. 57). But this view, which seemed so plausible, was rejected by all who know the Cambrian and Canadian carbonate sequence intimately.

The Cambrian and Canadian stratigraphic units maintain specific lithologic faunal characteristics along the whole length of the Taconic belt to such an extent that simultaneous deposition side by side in one narrow basin seems indeed improbable. The solution of the problem must lie elsewhere. Where, could be found only through further detailed mapping. The writer believes that enough has been accomplished to show the direction in which the baffling problem of the Taconic sediments will be solved.

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The three graptolite localities lie in the northeast rectangle of the Catskill quadrangle, on or near Highway 9, between 0.6 and 0.7 miles northwest of the intersection with a minor road near Humphreysville (Pl. 1, loc. 1) The lowest horizon is exposed in an abandoned quarry west of the highway. Here large specimens (up to 6 inches long) of *Dictyonema* and other multibranched forms occur in partings of black shale between thick limestone beds near the base of the exposure. A good collection of this and the other faunas is now in the New York State Museum.

The next-higher horizons, separated from the quarry section by a covered interval, are exposed in good road cuts. (*See* Ruedemann, 1942a, Figs. 26–28, p. 73–75). Here two contrasting rock types alternate rhythmically:

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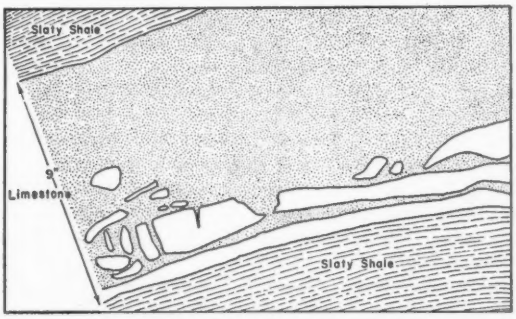

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The matrix is identical with that of the coarse limestone breccias interbedded here and elsewhere in Deepkill shales. Road cut southeast of Cherry Hill, Catskill quadrangle, New York.

coarse sand grains. These beds are lenticular, thickening locally from a few inches to as much as 3 feet in a distance of about 5 feet. Figure 2, which shows the base of one of these breccia beds, proves that part of the light-weathering limestone fragments did not come from far but resulted from the destruction of thin layers *in situ*. This points to the action of waves or currents (possibly turbidity currents), which swept in the coarse sand grains and probably part of the carbonate fragments. There are five such thicker breccia beds, in addition to several thinner limestones of the same general character. At two horizons, Flower found graptolite assemblages in shale layers. In both *Triograptus* was conspicuous. The lower also "contained dendroids, poorly preserved, but evidently a considerable variety of forms . . . which, at a guess and from memory, (may) include *Callograptus* and *Dendrograptus*" (Personal communication).

This outcrop is lithologically identical with that of the Schaghticoke shales at the type locality. (*See* Ruedemann, 1903, photograph on plate opposite p. 936.) The presence of *Dictyonema* in the quarry and of other dendroids here confirms a pre-Deepkill, *i.e.*, Schaghticoke age, for these beds (considered lowest Ordovician by Ruedemann).

The last of the three new fossil localities lies a short distance south, in the next exposure on the east side of Highway 9. Its beds lie stratigraphically above the preceding ones. Here Flower found *Didymograptus*, *Tetragraptus*, and *Phyllograptus*, *i.e.*, forms characteristic of the lowest graptolite beds that in places are very calcareous and are associated with greenish and grayish shales, resembling the lower Cambrian shales" (1930, p. 87). However, at the type locality, only the lower 59 feet of the continuous section (zones b to 1) consists of limestone, including two horizons 14 and 16 feet thick respectively; breccia bands are intercalated at several levels in the greenish-gray, hard, siliceous zones; and the lower layers of zone c, about 5 feet above the base of the section, "contain numerous small, angular pebble of limestone and black hornstone in such quantities that these appear brecciated" (Ruedemann, 1902, p. 547).

Here, then, an apparently continuous sequence represents the Schaghticoke-Deepkill-time interval, with a thickness that exceeds 100 feet and may measure 200 feet. This fine section compares with the total thickness of the type sections of the Schaghticoke (30 feet minimum; "probably considerably more") and Deepkill shales (170 feet) (Ruedemann, 1942a, p. 79–80).

The lowest Ordovician shales of the Taconic sequence are, thus, so similar to the lithologies of the Lower Cambrian that they can be easily confused. It is not a question of one trick exposure chancing to have a deceptive look. The whole complex mimics characteristic lithologies of the Nassau and Schodack formations. It is,

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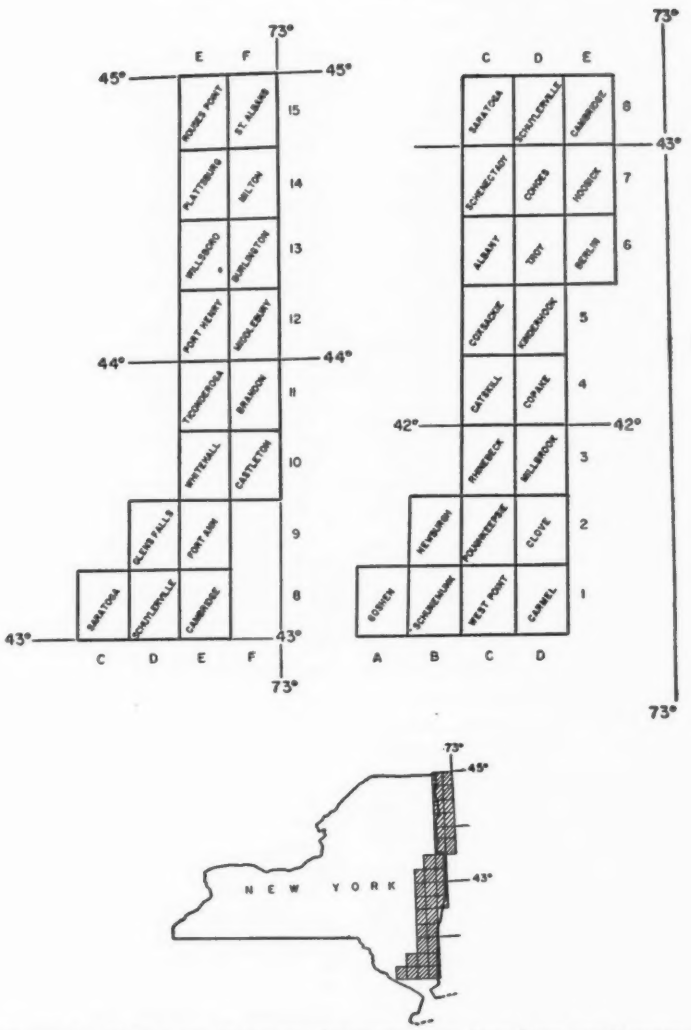

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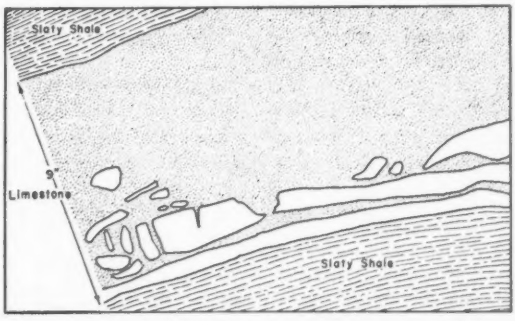

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This outcrop is lithologically identical with that of the Schaghticoke shales at the type locality. (*See* Ruedemann, 1903, photograph on plate opposite p. 936.) The presence of *Dictyonema* in the quarry and of other dendroids here confirms a pre-Deepkill, *i.e.*, Schaghticoke age, for these beds (considered lowest Ordovician by Ruedemann).

The last of the three new fossil localities lies a short distance south, in the next exposure on the east side of Highway 9. Its beds lie stratigraphically above the preceding ones. Here Flower found *Didymograptus*, *Tetragraptus*, and *Phyllograptus*, *i.e.*, forms characteristic of the lowest graptolite beds that in places are very calcareous and are associated with greenish and grayish shales, resembling the lower Cambrian shales" (1930, p. 87). However, at the type locality, only the lower 59 feet of the continuous section (zones b to 1) consists of limestone, including two horizons 14 and 16 feet thick respectively; breccia bands are intercalated at several levels in the greenish-gray, hard, siliceous zones; and the lower layers of zone c, about 5 feet above the base of the section, "contain numerous small, angular pebble of limestone and black hornstone in such quantities that these appear brecciated" (Ruedemann, 1902, p. 547).

Here, then, an apparently continuous sequence represents the Schaghticoke-Deepkill-time interval, with a thickness that exceeds 100 feet and may measure 200 feet. This fine section compares with the total thickness of the type sections of the Schaghticoke (30 feet minimum; "probably considerably more") and Deepkill shales (170 feet) (Ruedemann, 1942a, p. 79–80).

The lowest Ordovician shales of the Taconic sequence are, thus, so similar to the lithologies of the Lower Cambrian that they can be easily confused. It is not a question of one trick exposure chancing to have a deceptive look. The whole complex mimics characteristic lithologies of the Nassau and Schodack formations. It is,

therefore, no longer permissible to assume a Lower Cambrian age, merely because exposures look like "Nassau" or "Schodack." These formations have been reported from the quadrangles south of Catskill, New York, on the strength of lithologic similarity. Such age assignments are doubtful since no Lower Cambrian fossils have been reported south of Walcott's locality in the northeast corner of the Catskill quadrangle (Pl. 1, loc. 2).

Bona fide Lower Cambrian in the Taconic facies emerge along the thrust fault shown on Goldring's geologic map of the Coxsackie quadrangle (Fig. 1, C5) and can be traced, well documented by fossils, from excellent exposures on the east side of the Hudson north of Poolsburg (Pl. 1, loc. 3) to Troy (Pl. 1, loc. 4) and northward. Southward this "Troy thrust" seems to divide into two branches before it enters the Catskill quadrangle (Fig. 1, C4), the western "Burden thrust," and the eastern "Cherry Hill thrust." The throw diminishes on both, bringing Deepkill opposite Normanskill, and both die out in the Normanskill shale.

It may be tentatively suggested, as a working hypothesis, that the "Taconic facies" of the Lower Cambrian takes the place of the Poughquad-Stissing facies away from the margins of the Precambrian "highs." A distance of well over 35 miles separates the northernmost Lower Cambrian sequence on Stissing Mountain (NW. rectangle, Millbrook quad.) from the nearest beds of Taconic facies documented by fossils, between Poolsburg and Schodack Landing on the Hudson River (Pl. 1, loc. 3). In the next tier of quadrangles to the east, in the Kinderhook quadrangle, the southernmost Lower Cambrian fossils have been reported from about the same latitude (Pl. 1, loc. 5, 6). Southward, the Lower Cambrian formations seem to disappear beneath shales of the Schaghticoke-Deepkill sequence which rest on them with a large unconformity. (*See* Geologic Map, Ruedemann, 1930.) A similar situation was recently demonstrated in the Leirs-Chaudière area of the lower St. Lawrence Valley (Rasetti, 1946, p. 703–704).

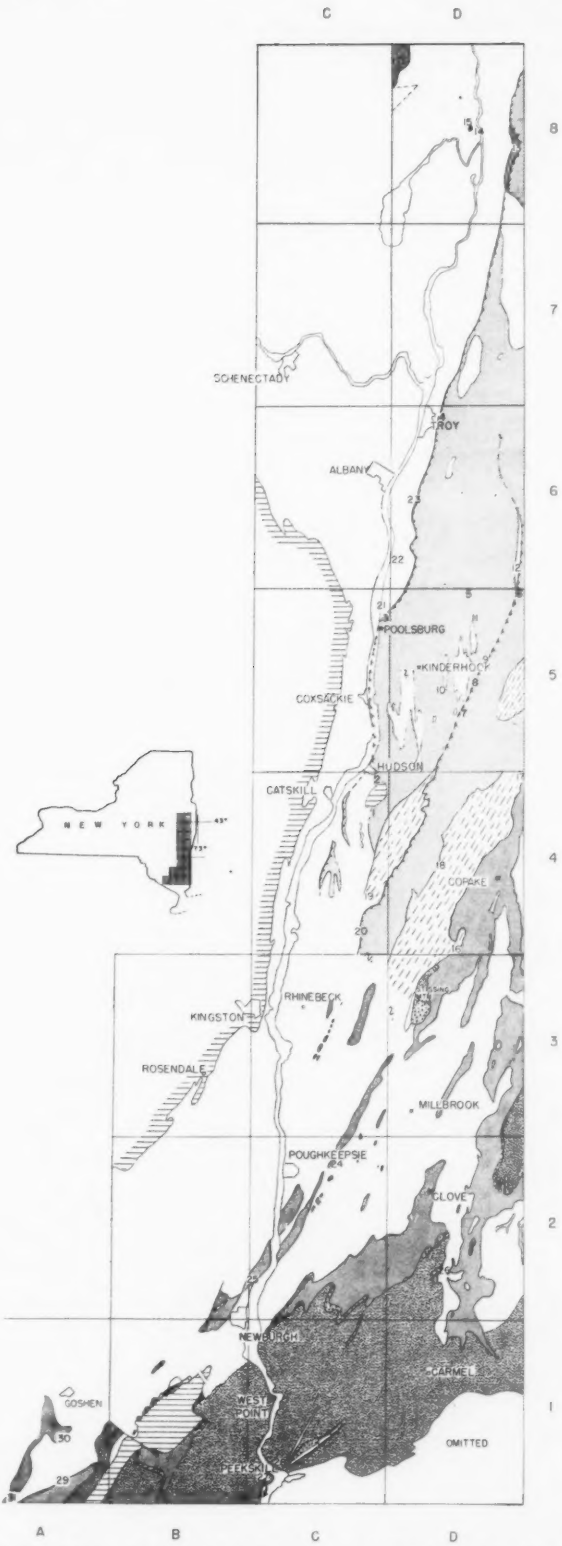
The presence of an unconformity between the Lower Cambrian and the Ordovician sequences caused no special comment while they were assumed to have existed in a separate trough east of the carbonate sequences. But if they belong in the same belt as the Upper Cambrian and Canadian carbonates, then the problem of their relationship becomes acute.

2. *Evidence Suggesting That the Carbonate Sequence Lies between the Lower Cambrian Formations and the Unconformity at the Base of the Schaghticoke-Deepkill Sequence*

a. Evidence from the Kinderhook quadrangle.—Craddock (1957) found rather massive, light-gray-weathering limestone carrying Canadian (Rochdale) fossils (*Lecanospira, etc.*) interbedded with brown-weathering gray dolomites in six small areas lined up along the Chatham thrust in the Kinderhook quadrangle (Pl. 1, loc. 7, 8, 9). He came to the conclusion that they are resting essentially in place on top of the green siliceous Lower Cambrian shales. The writer has examined the localities and is convinced Craddock is correct, though their position appears disturbed so close to the thrust plane. This suggests the following relations.

(i) In the Kinderhook quadrangle, on the downthrow side of the Chatham thrust, the shales correlated with the Deepkill lie on Lower Cambrian (Pl. 1, loc. 10, 11, etc.). (ii) East of the thrust, the just-mentioned Lower Canadian (Rochdale) carbonates rest on Lower Cambrian, at about the same elevation above sea level as the Deepkill shales. But that position is due to the Chatham thrust. Originally they must have been at a lower level and, of course, some distance to the east. (iii) In the southeastern third of the southward adjoining Copake quadrangle (Fig. 1, D4), the Upper Cambrian carbonates must rest at depth directly on Lower Cambrian as they do throughout the autochthonous terrane. Above them follows a thick sequence of dolomites topped by the dolomites and limestones of the higher Canadian (Copake limestone). These relations are shown diagrammatically in Figure 3. It looks as if there were a progressive overlap of the carbonate sequence onto a broad anticlinal axis of Lower Cambrian and as if the "Taconic" shale sequence were, at least largely, younger than the youngest Canadian carbonates of the region and probably separated from it by an unconformity.

b. Evidence from the Troy quadrangle.—The appearance in the Kinderhook quadrangle of



GENERALIZED GEOLOGIC MAP OF THE HUDSON RIVER REGION BETWEEN THE LATITUDES OF SCHUYLERVILLE AND PEEKSKILL, NEW YORK

Marbled, Precambrian; *uniform coarse stippling,* Lower Cambrian, Nassau-Schodack facies; *coarse and fine dots,* Lower Cambrian, Poughquag-Stissing facies; *very fine stippling (gray tint),* Cambro-Ordovician carbonate facies; *blank,* Ordovician shale facies, undivided; *diagonal hachures,* young Trentonian black shale, distinguished only in the Copake and Kinderhook quadrangles; *horizontal ruling,* Siluro-Devonian sediments.

Locality numbers are referred to in the text.

carbonates, all of the same Lower Canadian age and similar lithologies, over a distance of some 15 miles, apparently lying on Lower Cambrian shales (Pl. 1, loc. 7, 8, 9), is in itself a strong argument for the overlap postulated. It is strengthened by the presence of a belt of

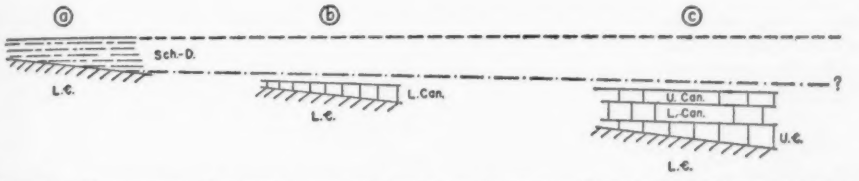


FIGURE 3.—HYPOTHETICAL RELATIONS BETWEEN SHALE AND CARBONATE SEQUENCES ON FLANK OF LOWER CAMBRIAN ARCH

carbonates of essentially the same lithology and age, another 10 miles farther north, in the Troy quadrangle. Here the main, lower part of the Tackawasick limestone borders the quartzites of the Rensselaer plateau (Pl. 1, loc. 12). The relation of the outliers of this quartzite to the surrounding shales south of its main body leaves little doubt concerning its Lower Cambrian age. If the carbonates farther south lie directly on the Lower Cambrian, the position of the presumably equivalent Tackawasick limestone (actually alternating dolomites and limestones) on the Rensselaer quartzite without evidence of the older members of the carbonate series need cause no surprise.

c. Evidence from the Schuylerville quadrangle.—Still farther north, members of the carbonate sequence make an unexpected appearance in the midst of "Taconic" shales, in the much-discussed "Bald Mountain limestone." Though the writer has not seen this important locality himself, he ventures to point out the following, solely on the basis of the geologic map of the Schuylerville quadrangle (Pl. 1, loc. 13) (Cushing and Ruedemann, 1914).

(i) On Bald Mountain, typical "Taconic" Lower Cambrian is thrust onto the "Bald Mountain limestone," which in its upper part carries a fauna characterized by gastropods (especially species of *Eccyliopterus*); this points to a Middle Canadian (Cotter?) age according to Flower (Personal communication, Feb. 7, 1947).

(ii) The "Bald Mountain limestone" is thrust onto the Normanskill shale (*e.g.*, on the southwest side of Louse Hill). Since under ordinary circumstances the beds which are "thrust up" on top of others that lie in front of them originally lay lower and stratigraphically below them, the simplest conclusion is that the Normanskill shale is younger than the limestone.

(iii) With one exception the base of the Normanskill is hidden by the Snake Hill shale which lies unconformably on the older formations (as will be shown below). In the small anticline which crosses the Hudson River above Schuylerville (Pl. 1, loc. 14), the Schaghticoke formation appears conformably below the Normanskill. (The anticline is sufficiently steep-sided to make it probable that the Deepkill shale is present between the Schaghticoke and Normanskill shales and is either not exposed or not recognized.)

The normal explanation of the presence of the "Bald Mountain limestone" is also the simplest: it underlies the Schaghticoke shale. This agrees perfectly with the presence of quantities of pure limestone fragments of the same "finely crystalline" texture as the "Bald Mountain limestone" in the small tongue of pillow lava exposed in Stark's Knob a little to the west (Pl. 1, loc. 15) (Cushing and Ruedemann, 1914, p. 121, 133; Colony, 1929, p. 172–190). Since such mild eruptive activity as that displayed at Stark's Knob may be expected to start close to the surface, shattering and engulfing the limestone and pushing aside the (then still soft) shale layers,[1] this occurrence serves as evidence that the "Bald Mountain limestone" immediately underlies the Schaghticoke shale.

(iv) West of Stark's Knob, the Normanskill

[1] Colony reports that the lava pillows, with a vitreous crust of dark volcanic glass, lie in a "shale matrix." In the solid portions, limestone constitutes about half the volume, and the limestone and lava are intermixed in a fashion difficult to explain.

shale is thrust onto the Snake Hill shale which is generally recognized as younger than the Normanskill shale.

This sequence is completely in harmony with the structural relations along the corresponding thrusts farther south.

d. General comments.—This points to the conclusion that the Upper Cambrian and Lower (and Middle) Canadian carbonates overlapped on the structural axis of Lower Cambrian rocks from the west as well as from the east, and that the Schaghticoke-Deepkill shale sequence transgressed across them unconformably, after further warping.

It is possible that locally shale facies took the place of the carbonate sequence even before the transgression. In that case shales would locally have been deposited in Upper Cambrian near the center of the basin simultaneously with carbonates along the margin. Such a condition is assumed by Weaver (1957), who points out the similarity of quartzites found intercalated in the carbonate sequence (Upper Cambrian Pine Plains dolomite) in the southeastern part of the Copake quadrangle (Fig. 1, D4) and in the Elizaville shale (of Schaghticoke-Deepkill age) in the central part.

In the south rectangle of the Copake quadrangle the two lithologies crop out within less than a mile of each other. A concealed thrust may lie between the two outcrops and would allow a little more room for the original space between them. Even so, the distance seems very short for a transition between two facies of such contrast, since the whole "Taconic" shale sequence from the Schaghticoke to the Normanskill is a conformable and consistent sequence like the equally conformable and consistent carbonate sequence.

It should be possible to demonstrate in the region south and southeast of the Copake quadrangle, where the Lower Cambrian "Taconic" axis plunges out of sight, that the Schaghticoke-Deepkill-Normanskill shale sequence belongs on top of the Canadian carbonates, as far as they are present along the axis. There, in the Rhinebeck (Fig. 1, C3), Millbrook (Fig. 1, D3), and Poughkeepsie quadrangles (Fig. 1, C2) this stratigraphic relation should be widely observable. There, indeed, shale sequences that look like typical Lower Normanskill and at least upper Deepkill are seen east of eastward-dipping "Wappinger" carbonates.

But if the relations are so simple, why were they not recognized as a matter of plain observation long ago? The answer lies in the presence of a much younger shale which lies with a profound unconformity on all the older rocks and conceals their true relations. The recognition of the large extent of this unconformity at the base of the "younger Trentonian shale" is thus, perhaps, the most important of the new facts here reported.

3. *Widespread Unconformity at Base of Younger Trentonian Black Shale*

a. Evidence from Copake to Schuylerville quadrangles.—An important result of detailed mapping in both the southern and northern parts of the Taconic belt is the recognition of an unconformity of major importance at the base of the Younger Trentonian black shale that has hitherto been included in the "Normanskill shale." Weaver first demonstrated it in the Copake quadrangle (Fig. 1, D4). Weaver's map (1957) shows a narrow band of limestone following the base of the "Trenton shale," with a few interruptions, from the center of the southern margin (Pl. 1, loc. 16) to the northeast corner (Pl. 1, loc. 17). It is a bluish-gray limestone, rather thin-bedded, which ranges from fine-grained uniform rock to one that is streaked and layered with coarse-grained material. Much of it has a crystalline appearance owing to quantities of included echinoderm (chiefly cystoid) plates. Locally there are also partings of quartz sand. It ranges in thickness from 0 to over 30 feet. Thin layers of similar limestone are interbedded in the base of the overlying black shale. Poorly preserved impressions of *Sowerbyella* and *Dalmanella* in thin sandy zones point to a Trenton age.

The limestone is absent along the northwest side of the younger Trentonian shale belt where it lies on the Elizaville shale (here probably of Schaghticoke and Deepkill age, along front marked by loc. 18 in Plate 1). This suggests that a slight oscillation of sea level removed all or most of the limestone from the old axis before the main body of the shale was deposited. But the time interval must have been short.

since the fossils suggest that the limestone is Trentonian also.

It is not surprising, therefore, to find a limestone conglomerate, with Trenton fossils in the pebbles as well as in the calcareous matrix, at the base of the same Trenton black shale along the western margin of the second belt, a short distance beyond the western border of the Copake quadrangle in the southeastern quarter of the Catskill quadrangle, about halfway between Manorton and Elizaville (Pl. 1, loc. 19). This is the southernmost exposure of Ruedemann's Rysedorph conglomerate which he placed at the base of the Snake Hill shale formation (Ruedemann, 1930, p. 113). It rests here on the Mount Merino member of the Normanskill. About 3 miles farther south-southwest, D. W. Fisher (Personal communication) has found Trenton limestone recently (Pl. 1, loc. 20).

Traces of the same conglomerate horizon are found farther north at two places in the Coxsackie quadrangle, at Schodack Landing and three quarters of a mile south of it (Pl. 1, loc. 21) (Goldring, 1943, p. 123). These localities line up with the belt in which the same fossiliferous Trenton conglomerates crop out in the Albany and Troy quadrangles, from Moordener Kill near Castleton (Pl. 1, loc. 22), northward on the east shore of the Hudson to Rysedorph Hill (Pl. 1, loc. 23). Unfortunately this important belt is not distinguished on the geological map by a separate symbol or color, and its presence s not evident to the eye. It lies 1–2 miles west of the Troy thrust, running roughly parallel with it. Much of the black shale associated with it in that interval must belong to the transgressive younger Trentonian shale belt.

The corresponding belt on the Catskill quadrangle, mentioned above, lies close to what seems to be the southern extension of the Chatham thrust. This spatial relation is typical. In belts between parallel thrust planes, the youngest beds tend to occur along the feet of the overriding thrust plane. For the same reason, the Rysedorph conglomerate lies close to the thrust plane on which the Lower Cambrian overrides the carbonate zone on Bald Mountain, in the Schuylerville quadrangle (Pl. 1, loc. 13).

At all the localities mentioned, scattered over a distance of 75 miles, fragments in the conglomerate range from well-rounded pebbles to subangular "sharpstones" derived from the immediate vicinity. Thanks to Ruedemann's classical study of these conglomerates, the source of the fragments is known.

(i) North of Elizaville, in the Catskill quadrangle (Pl. 1, loc. 19), "the majority of the pebbles . . . are limestone of Trenton appearance" (Ruedemann, 1942a, p. 123). This suggests that earlier Trenton limestones had been deposited here and were largely destroyed as the overlying younger black shale transgressed.

(ii) At Schodack Landing (Pl. 1, loc. 21), pebbles of grayish or reddish sandstones dominate. Since similar sandstones are common in the true Normanskill shale in which the conglomerate lies, it is most likely that they were derived from them, though the Potsdam or horizons of Canadian sandstones are a possible source. In addition, there are "large boulders of Lowville limestone, up to 1½ feet in diameter," identified by the presence of *Tetradium cellulosum* (Hall), and smaller pebbles with fossils of lower Trenton age (Ruedemann, 1901, p. 8–9). Since the Lower Trenton pebbles may be assumed to have been locally derived, like those of Elizaville, it seems likely that the large boulders of Lowville mark remains of a thin layer deposited on the axis of older rocks in a brief transgression before Trenton time.

(iii) Farther north, at the type locality (Pl. 1, loc. 23), a greater variety of horizons is represented among the pebbles. The old structural axis has furnished lower Cambrian limestones with *Hyolithellus* and sandstones presumably from both Lower Cambrian and Schaghticoke-Deepkill and Normanskill shales. But in addition, black crystalline limestone with characteristic Chazyan fossils and dense light-colored Lowville limestones with *Tetradium* are found among a vast majority of fragments carrying rich Lower Trenton faunas[2] (Ruedemann, 1930, p. 105–113).

[2] Since Ruedemann thought of the whole shale sequence, including the Snake Hill shale, as heaved onto the carbonate sequence from the east, he was puzzled by the fact that "with the exception of the lower Cambrian limestone, none of the groups of pebbles with their faunas can be referred to ledges of rock in eastern New York or the neighboring parts of Vermont and Massachusetts." He tried to explain this by assuming that the eastern counterparts are concealed by metamorphism and are to be sought in the marbles of the marble belt. Kay recognized the fallacy and saw clearly that the Snake Hill shale cannot be exotic (Kay, 1937, p. 277).

(iv) Finally, along the foot of Bald Mountain (Pl. 1, loc. 13), in the Schuylerville quadrangle where the Lower Cambrian shales of the old axis have been thrust onto dolomites and limestones of its western flank, the Rysedorph conglomerate contains largely pebbles of Lower Cambrian limestone and dolomites and limestones of the carbonate sequence, with only a "few pebbles" carrying Lower Trenton fossils. Here again, as in all the other localities, "the smaller pebbles are well rounded, the larger ones subangular with rounded edges" (Cushing and Ruedemann, 1914, p. 80).

These details are given to show that the composition of the Rysedorph conglomerates is largely influenced by their near-by environment. They are, therefore, truly "basal conglomerates" of the transgressing younger Trentonian black shale. In transgressing, they encountered (or left) erosion remnants of relatively thin layers of Black River (possibly) and Lower Trenton limestones that had overlapped intermittently onto the axis.

b. Evidence from the Capital district to the Canadian border.—In the western part of the Saratoga quadrangle, the Amsterdam limestone rests unconformably on the Little Falls dolomite (Fig. 1, C8). It must have cut across the intervening shale formations, if they were part of the sequence, in which case similar unconformable relations should exist at the base of the Snake Hill shale in places where there is no Amsterdam limestone present. Evidence of this does exist. At two places, close to the lower contact with the Normanskill shale,[3] Ruedemann found "compact grit and conglomerate beds one to four feet thick," in the Snake Hill shale. The conglomerate contains well-rounded pebbles of shale, black limestone, whitish chert typical of Normanskill shale, and milky quartz. There are also "beds of gray, crystalline, often sandy limestone. . . . All the rocks of this locality, the shales, the limestone band, the grits and the conglomerates, are fossiliferous and besides a few graptolites furnish cystoids, crinoids, brachiopods, gastropods, pelecypods and trilobites" (Cushing and Ruedemann, 1914, p. 95). The pebbles of Normanskill chert, shales, and black limestone prove the presence of an erosion unconformity at the base of the Snake Hill shale.

Along the south foot of the Adirondacks, some 48 miles northwest of Rysedorph Hill, at Sprakers (about halfway between Albany and Utica, New York), coarse-textured limestones of lowest Sherman Fall age with interbedded dark shales grading upward into Canajoharie black shale, lie unconformably on Beekmantown limestone. Rounded and angular blocks of Beekmantown limestone up to 2 feet in diameter are common near the base, and smaller, flat pebbles in the overlying beds (Kay, 1937, p. 264).

Some 20 miles northeast of Rysedorph Hill, on Mount Anthony near Hoosic, New York, a Trenton limestone that grades upward into dark slate rests apparently on Canadian limestones (Walcott, 1888, p. 238). Bald Mountain, some 20 miles northwest of Mount Anthony, in the Schuylerville quadrangle (Pl. 1, loc. 13) carries the unconformity across the Taconic axis.

Farther northwest, in the Fort Ann quadrangle, west of the axis, Trenton limestone lies unconformably on Beekmantown formations of Fort Cassin and Smith Basin age (Flower, personal communication).

Still farther northeast, in the Castleton, Vermont, quadrangle, fossiliferous Trenton limestone was reported as early as 1877 by Wing[4] from the heart of the "great central belt of slates" (Dana, 1877, p. 340). Wolff (1891, p. 336) and Foerste (1893, p. 441–442) found Trenton limestone locally 30 feet thick and resting on the Stockbridge limestone, grading upward into dark shales. Bain reported a good fauna from the blue-gray limestone above the same unconformity at West Rutland (Bain, 1938, p. 10) where it lies on the Chazyan Beldens formation (Fowler, 1950, map). Cady recognized the importance of this unconformity (Cady, 1945, p. 559–560). In mapping the Castleton quadrangle, Fowler traced the same limestone southward east of West Rutland and

[3] Along the anticlinal axis that brings the Normanskill shale to the surface on the east side of Saratoga Lake over 4 miles northeast of a promontory near south border of map.

[4] Wing "found the *Trinucleus concentricus* 10 miles SE of Sudbury . . . in Hubbardton, in a limestone 60 yds. inside the heart of the 'great central belt'; and also farther south, 1 or 2 miles north of the slate quarries of west Castleton" (Dana, 1877, p. 840).

shows it cutting unconformably from the Lower Canadian "Boardman formation" across the Upper Cambrian Clarendon Springs dolomite onto the Upper Cambrian Danby formation. In the northwest corner of the map it rests on the Orwell limestone, the youngest of the underlying formations (Fowler, 1950, map). But here, as wherever it has been studied in detail, the limestone is not everywhere present at the base of the dark shales or phyllites into which it grades upward. Over large stretches the shale rests directly on the underlying older rocks.

The role which this unconformity has played in the development of the Taconic thrust concept has been clearly set forth by Cady (1945, p. 560) and Fowler (1950, p. 36). Since the writer has seen this northern region only twice on short visits, he does not venture into a discussion of the "klippe" concept here. (*See also* Kaiser, 1945, p. 1094–1096.)

That this unconformity extends to the Canadian border is shown by the Lacolle conglomerate (Clark, 1934, p. 5; Clark and McGerrigle, 1936, p. 666–674). It lies unconformably on Beekmantown, Chazyan, and lower Mohawkian beds; it consists of boulders of dolomites and limestones, many with fossils, ranging from Beekmantown to Lower Trenton in age, up to several feet in diameter, in a matrix of sandy limestone; and it grades upward into black shale which Kay (1937, p. 275) assigns to the younger Trenton (late Sherman Fall). The polymict character of this conglomerate and its distribution along an unconformity traceable for over 6 miles (Clark and McGerrigle, 1936, p. 669) prove that this cannot be a "fault breccia" as has been suggested recently (Marshall Kay, personal communication).

c. Evidence from Catskill quadrangle south.— The unconformity at the base of the younger Trentonian black shales, in many places with a local blue-gray basal limestone, is seen south of the New York Highlands.

(i) Limestone conglomerates with a good Trenton fauna at the base of black shales are well exposed in the Poughkeepsie quadrangle along the east side of the "Wappinger limestone" belt that lies west of and parallel to Wappinger Creek (Pl. 1, loc. 24). They lie on top of Beekmantown dolomites with an uneven erosion surface. The presence of Trenton fossils in the Rochdale region was already known to Mather 100 years ago. Details and references to the earlier literature are given by Gordon (1911, p. 61–67). The same basal conglomerates crop out conspicuously west of the Hudson River in the Newburgh quadrangle (Pl. 1, loc. 25), at the base of the shales in the limestone anticline north of Balmville where it was first recognized by Dwight in 1880 (Dwight, 1880, p. 35; for details and illustrations *see* Holzwasser, 1926, p. 36–41).

(ii) Similar calcareous beds at the base of the younger Trentonian have recently been recognized by one of the writer's students (Larsen, 1953, M. A. Thesis, Columbia Univ.) on the Goshen quadrangle (Pl. 1, loc. 29, 30, 31), 1¾ miles northeast of Warwick, some 25 miles southwest of the Balmville type locality.[5]

The Balmville limestone here rests on coarse-grained, gray, massive Beekmantown dolomite with scattered black chert nodules. The basal beds rest on an uneven erosion surface and range accordingly in thickness from 3 to about 5 feet. They consist of light-colored, somewhat pinkish, platy limestone made up largely of fragments of ostracod and brachiopod shells and bryozoan and crinoid skeletons. Angular fragments of black chert like that in the underlying dolomite, up to ¼ inch in size, are plentiful. Five genera of ostracods collected by Larsen from this horizon were identified by J. M. Berdan of the U. S. National Museum. They represent a "Middle Ordovician" assemblage.

The next 20 feet are rather thin-bedded, almost black crystalline (crinoidal) limestone, above which begins the younger Trentonian black shale. In another exposure, about 3¼ miles west of Warwick, the unconformity at the base of the limestone reaches a relief of 8–10 feet; and there is less limestone than at the first exposure. Four miles north of the latter, the Balmville limestone is absent, and the black shale rests directly on the dolomite. Rounded boulders several feet in diameter and smaller cobbles lie at the base of the black shale and are partly or wholly enveloped by it.

Here, then, within a few square miles, is the same condition found farther north; the lime-

[5] On Ries' geologic map of Orange County this limestone is called Devonian-Helderberg (Ries, 1898, map). This created difficulties for structural interpretation which were "solved" by means of a hypothetical thrust fault.

stone at the base of the black shale is not continuous but present only in irregular areas as if they were erosion remnants.

(iii) About 20 miles east of Warwick, on the opposite side of the New York Highlands, dark-gray calcareous beds beneath the same black shales lie on top of unfossiliferous Cambro-Ordovician dolomites at the northeastern end of the quarries at Tomkins Cove, in the southwest corner of the West Point quadrangle (Pl. 1, loc. 27). Here fossil remains are reduced to "crinoid" (probably largely cystoid) plates that lie scattered, or in streaks, in the fine-grained matrix. The weathered surfaces of the old railroad cut of the West Shore Railroad north of the quarry show the limestone streaked with coarse quartz sand and grit. Thin sections show other mineral grains, especially sericite, derived from crystalline rocks, and much opaque carbon (or carbonaceous material) and pyrite. The limestone grades upward into the black shales through a zone of interbedded thin limestone beds and shale.

The deformation is intense, and in the gray limestone a strong lineation in the direction of the dip (in *a*) is developed on the bedding planes. The normal dark color of the rock is changed to white in irregularly spaced, elongated streaks, 1 foot to several feet wide, aligned in the *a* direction.

The same dark-gray limestone with much wider and more striking white, completely recrystallized zones, is seen again on the east side of the Hudson River in a remarkable exposure on U. S. Highway 9, a road cut about a quarter of a mile south of Annsville, on the west side of Peekskill Creek, northwest of the town of Peekskill (West Point quad., Pl. 1, loc. 28). Here the limestone is preserved in a narrow syncline tightly infolded in Precambrian gneiss (Dincer, 1951, M.A. Thesis, Columbia Univ., p. 31, 32). The contact between the gray limestone and the crystalline basement was well shown on a glaciated surface which was exposed in a sand pit about 1000 feet farther south in the midst of gravel and sand (glacial outwash). Road building has destroyed that locality but has provided a different exposure in the new road cut.[6] At both places the limestone penetrates into crevices and other irregularities of the gneiss surface, showing evidence of plastic flow characteristic of limestones subjected to tectonic deformation (Pl. 2, fig. 1).

Here, in direct contact with the crystalline basement, the limestone contains not only sand but detrital fragments up to over 1 foot in diameter and representing a great variety of rock types, including banded gneiss (Pl. 2, fig. 2), hornblende schist, "greenstones," quartzites and dolomites (Pl. 3, fig. 1), and granitoid gneiss (Pl. 3, fig. 2). The sand-sized particles comprise, of course, all the minerals represented in the pebbles.

On the glaciated surface, from which the four illustrations on Plates 2 and 3 were taken, the bedding was well shown and in places even took the form of rather fine laminations. The polymict character of the breccia and the small number of larger fragments prove that this is a sedimentary breccia and not a mylonite, especially as no limestone was available to furnish the calcitic material.

Four lines of evidence justify the statement that this gray limestone is indeed the same as that exposed on the west shore of the Hudson River at Tompkins Cove: both are associated with the black shale, though on Highway 9 the two are not in immediate contact, owing to

[6] The writer owes special thanks to T. W. Fluhr for calling his attention, through Kurt Lowe, to the sand-pit locality when the limestone had been laid bare by excavation in 1948. The writer (Bucher, 1951) visited the place in January, 1949, and took photographs (with a Leica camera), several of which are here reproduced.

PLATE 2.—GRAY TRENTON LIMESTONE FULL OF DETRITUS DERIVED FROM CRYSTALLINE ROCKS, INFOLDED IN PRECAMBRIAN GNEISS

FIGURE 1.—Gray Trenton limestone resting unconformably on Precambrian gneiss. Note intense deformation of basement and limestone. Former sand-pit exposure on U. S. Highway 9, west of Peekskill Creek, near Peekskill, New York (Bucher, January 1949).

FIGURE 2.—Gray Trenton limestone rich in detritus derived from basement, including scattered pebbles. Note bedding, indicated by darker bands, inclined to left, and glacial striae inclined to right. Former sand-pit exposure on U. S. Highway 9, west of Peekskill Creek, near Peekskill, New York (Bucher, January 1949).

FIGURE 1

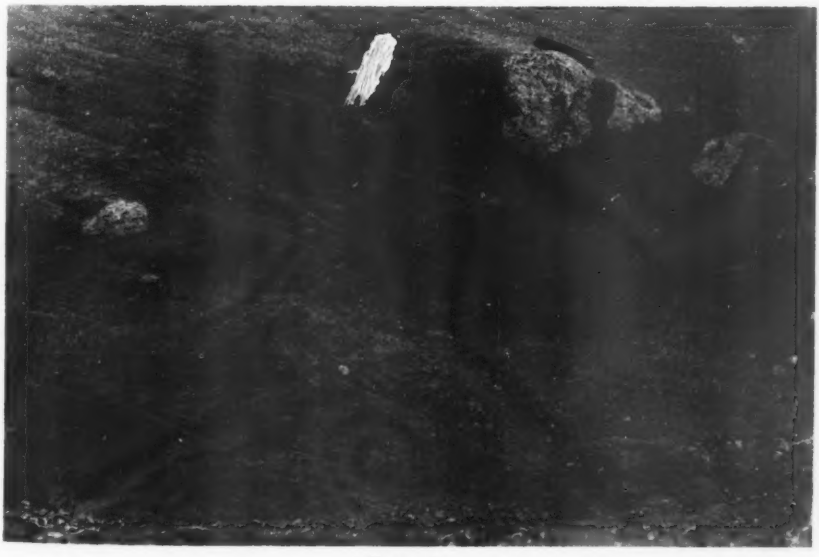


FIGURE 2

GRAY TRENTON LIMESTONE FULL OF DETRITUS DERIVED FROM CRYSTALLINE ROCKS, INFOLDED IN PRECAMBRIAN GNEISS

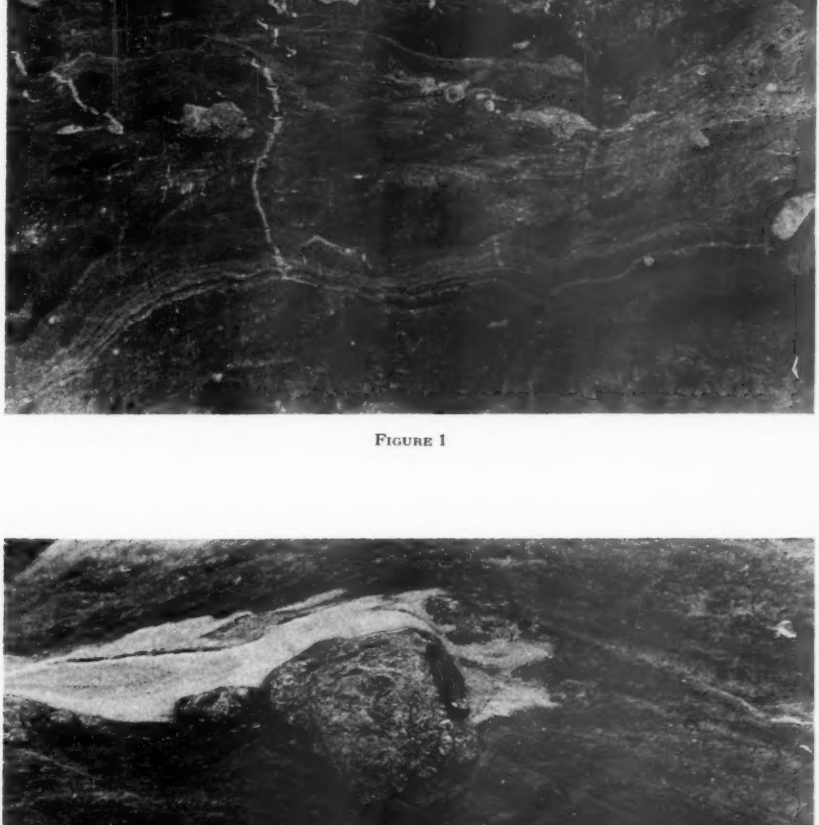


FIGURE 1

FIGURE 2

DETRITUS DERIVED FROM CRYSTALLINE ROCKS IN GRAY TRENTON LIMESTONE INFOLDED IN PRECAMBRIAN GNEISS

faulting and erosion; both contain cystoid fragments recognized readily by their characteristic texture; both are rich in carbon where not subsequently altered; and in both, the rock is partially recrystallized to a white marble.

The manner in which the recrystallization to white marble has taken place along Highway 9 is significant. In the former sand-pit exposure, which lay south of the new road cut, streaks of white marble appeared scattered through the gray limestone, larger and better defined than those seen north of Tomkins Cove but essentially of the same type. One such streak shows conspicuously on Figure 2 of Plate 3 and looks like snow. It parallels the bedding roughly. It appears suddenly and ends the same way (beyond the picture's border). Note especially that in that part of the contact with the gneiss which is shown in Figure 1 of Plate 2, there is no recrystallization whatever, although there is at other points.

About 1000 feet farther north, in the highway cut, about half the limestone exposed is white marble. One and one-third miles farther northeast, in an old quarry, on the east side of Canopus Creek, all the limestone is massive-looking, coarse-grained, white marble.[7] As in its southward continuation, the limestone here also contains much clastic material, including metamorphic rocks and especially large rounded cobbles of coarse-grained dolomite and blocks of a coarse quartzite. Some layers are full of rounded grains of dolomite, 2–5 mm in diameter, derived from an older dolomite.

The cut on Highway 9 must accordingly lie just about on the line that separates unrecrystallized from recrystallized young Trenton limestone. The transition is, thus, here achieved within a distance somewhat greater than the near-by 2 miles that separate the highway cuts from the quarry on Canopus Creek. This agrees well with Balk's observation on the north side of the Highlands, where "the transition from the fossiliferous . . . dolomitic limestone to . . . recrystallized marble takes place within a distance of three miles." (Balk, 1936, p. 718). The line which connects the centers of these two transition zones north and south of the Highlands has the same trend as the anticlinal axes of Cambro-Ordovician dolomites shown on the geological map which accompanies Balk's classical study (1936, Pl. 1).

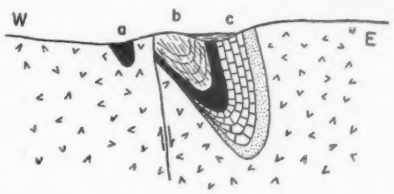


FIGURE 4.—DIAGRAMMATIC CROSS SECTION OF THE PALEOZOIC SEDIMENTS INFOLDED IN THE PRECAMBRIAN GNEISS NORTHWEST OF PEEKSKILL

Shows the westward overlap of the young Trentonian limestone and shales (eroded on left) onto the gneiss. At "a", the cut described here; at "b", the Annsville cut. Poughquag ss., dotted; E-O dol.-ls. series, cross bars; Trenton ls., black; black sh. in center of syncline.

Here, then, the basal limestone lies directly on the Precambrian gneisses of the Highlands. Figure 4 shows the broader relations of the Highway cut to the phyllites and carbonates exposed to the east in Peekskill Hollow as the writer interprets them. The pre-Trentonian warping must, therefore, have gone even farther in the south than in the north, allowing erosion to cut down to the crystalline core of the Old Precambrian highs before the young

[7] Because of its coarsely crystalline character and its position as a band in the gneiss, Berkey and Rice (1921, p. 105–106) referred this white marble to the Grenville. Note that "Sprout Brook" is Canopus Creek. See physiographic diagram, opp. p. 144, and geologic map.

PLATE 3.—DETRITUS DERIVED FROM CRYSTALLINE ROCKS IN GRAY TRENTON LIMESTONE INFOLDED IN PRECAMBRIAN GNEISS

FIGURE 1.—Detail of gray Trenton limestone full of detrital matter. Note laminations between coarser layers and diversity of rock materials in latter. Former sand-pit exposure, on U. S. Highway 9, west of Peekskill Creek, near Peekskill, New York (Bucher, January 1949).

FIGURE 2.—Gneiss boulder in Gray Trenton Limestone. Note (1) bedding curving around boulder; (2) white streak along which limestone is recrystallized to white marble; (3) glacial striations, inclined to right. Former sand-pit exposure on U. S. Highway 9, west of Peekskill Creek, near Peekskill, New York (Bucher, January 1949).

Trentonian sea transgressed onto it and probably across it.

Repeated upwarp, erosion, and transgression since the Lower Cambrian is clearly indicated by Balk's geological map (Balk, 1936, Pl. 1). On it the carbonate sequence ("Wappinger limestone") and the "Hudson River pelite" are shown extending into the Highland gneiss belt in the form of irregular lobes and erratic slender prongs, the carbonates overlapping the basal quartzite and the "pelites" the carbonates. This pattern, produced where successive formations transgress across an irregularly warped and eroded land surface, is well shown on geological maps of the central Ozarks where carbonate formations of similar age bear the same relation to the crystalline basement. There is the same "cutting out" of basal formations and disharmonious overlap of formations which simulates faulting, with advance toward the central part which originally must have been highest.

In the Ozarks there is no doubt about the nature of the disharmonious contacts, because the Ozarks were not caught in later orogenic movements which have disguished the primary unconformable relations. That is what has happened in the New York Highlands. The post-Trentonian orogenies (or orogeny) have affected the old crystalline basement as well as the overlying sediments. It has transformed the original, rather shallow depressions of the surface into sharply pinched-in synclines, squeezing the bulk of the sediments differentially upward and outward along the contact with the basement and along bedding and shear planes, imposing a lineation in the direction of the dip (in *a*) that contrasts sharply with the lineation parallel to the fold axes (in *b*) which is widespread in folds where there is no differential movement between beds or planes of shear. Balk has given valuable detailed descriptions of these structural details (Balk, 1936, p. 741–748). But he tends to look on them as indicators of "thrusting," but in an unusual usage of that term. In fact, on Balk's map the symbol for "faults and thrust faults" is used simply as a sort of shorthand to indicate breaks in the normal stratigraphic sequence. It follows the gneiss border in and out all the indentations and around all the prongs, except where the Poughquag quartzite lies in broad contact with the basement. This sort of "fault" contact exists only as the trace of an essentially horizontal thrust plane at the base of a thrust sheet. Such an interpretation, however, seems impossible in the light of the larger structural relations of the Highland gneiss in New York and New Jersey and of detailed observations in the water tunnels and at the surface. This "fault line," therefore, rather marks the zone of differential movement along contacts and shear planes produced by the pinching and squeezing of the sediments in the old depressions.[8] These "pseudo-thrust" zones will have to be studied in great detail after the stratigraphy of the metamorphosed carbonates and "pelites" has been established. Even the thrust fault at Whaley Lake, on the Clove quadrangle (Pl. 1, loc. 26), of which Balk gives a detailed description with block diagrams (Balk, 1936, p. 746–747) is probably another example of the young Trentonian shale overlapping onto the gneiss. The fact that it is limestone and not dolomite that underlies the "pelite" seems significant.[9] The metamorphism makes such interpretation more difficult, of course.

Summary: An Alternative Hypothesis

The tentative hypothesis, developed by the writer with the co-operation of Weaver and Craddock, which emerges from the above, is applied, for the present, only to that part of the Taconic belt that extends south from Bald Mountain in the Schuylerville quadrangle to the New York Highlands. It is possible that farther north a thrust of larger throw exists than is seen farther south and that folding has produced a "half klippe." The hypothesis may be summarized as follows:

(1) The Lower Cambrian sediments transgressing across the Precambrian unconformity

[8] That pinched-in synclines are very real was found out in the course of the drilling explorations in connection with the Delaware Water Tunnel and succeeding tunnel constructions—*e.g.*, in the drilling on Wickopee Creek, on the north border of the West Point quadrangle, on 73°50′ meridian (T. W. Fluhr, personal communication).

[9] The second quartzite (Balk, 1936, Fig. 33, p. 747) which overlies the limestone and for a distance even has some shale below it may well turn out to be a sandstone layer in the shale. Should one not expect such sandstone lenses in shale that transgresses across a basal quartz sand such as the "autochthonous" Poughquag?

were deposited on a warped surface of some relief. In the shallow water along the shores of the higher elevations of that surface, the basal clastic series developed as pure quartzites, while in the somewhat deeper water over the larger lower regions, shales with quartzite layers of the "Taconic" type were laid down. These were followed, probably throughout the region, by Lower Cambrian dolomites with shales, at least at the base, as in the "Taconic" Schodack formation.

(2) A first epoch of warping produced the Taconic structural axis along which the Lower Cambrian dolomites were largely removed by erosion.

(3) A second transgression (with occasional regressions that produced diverse disconformities) led to the formation of the carbonate series from the Upper Cambrian dolomites to those of the Lower Canadian (Gasconade).

(4) A second epoch of warping accentuated the Taconic structural axis, removing most of these carbonates from its higher parts, so that the beds of the older carbonate sequence lie only along the flanks and on the plunging southern part of the axis.

(5) Lessened uplift permitted some Middle Canadian formations to escape erosion here and there on the axis.

(6) In late (or very late) Canadian time, differential uplift ceased, the whole Taconic region became submerged, and shale took the place of the carbonates over the whole region. At first the waters were relatively shallow, and limestones and shales were laid down together with much sand. Limestone conglomerates formed perhaps largely through submarine sliding and intraformational flowage owing to rapid and unequal accumulation of sediments (Schaghticoke and Deepkill shales). Then with increasing depth of water, radiolarian cherts and graptolite shales accumulated (higher Deepkill and true Normanskill). Influx of sand (rich in shale fragments) heralded renewed uplift of the old axis (Austin Glen member).

(7) For a third time the old axis was rejuvenated, and erosion (perhaps wave erosion attacking shallows and islands) removed much of the "Taconic" shale sequence from large parts of the axis.

(8) The same interplay of intermittent submergence and emergence led to the deposition and partial removal of early Trentonian (and perhaps even Black River) limestones on the axis which appear as the basal limestones of the young Trentonian shales that follow.

(9) In young Trentonian time, deposition of shales was resumed and produced the Canojaharie-Snake Hill suite of black shales to be followed by coarser sediments which do not concern the present problem.

Nothing was said above about the problems of correlation that arise from this hypothesis. The writer must leave this to those who are competent to judge. But a few comments must be made. There has been a steady tendency to move the Deepkill and Normanskill shales up in the geological time scale. This is fully discussed by Dunbar in the text that accompanies the Ordovician correlation chart (Dunbar, 1954, p. 255–256). He offers good reason for assigning the Deepkill to the Chazyan. This agrees well with the results of Mrs. Ross' studies on Deepkill conglomerates (1948, M. A. Thesis, Cornell Univ.; 1949). The value of her findings depends on the reliability of certain textural or "algal" features as diagnostic of specific stratigraphic horizons. Too little work has been done on the microscopic characteristics of all the carbonates in the Cambro-Ordovician sequence to justify far-reaching conclusions.

The chief doubt attaches to the correlation of the Schaghticoke shales. *Dictyonema flabelliforme* is generally accepted as diagnostic of the "transition zone" from the Cambrian into the Ordovician, because it is found in Europe and America associated with trilobite genera of Upper Cambrian affinities. But this does not mean that it and other faunal elements associated with it did not survive for some time into the early Ordovician. No trilobites and especially no Cambrian trilobites seem to have been found with *Dictyonema* in the Schaghticoke beds. Even if this *Dictyonema* were identical with *D. flabelliforme*, which is by no means proved, it and other forms characteristic of the lowest graptolite zones may well have existed longer, possibly through latest Lower and Middle Canadian time. This appears plausible especially if the lowest Deepkill fauna is placed as high as the Chazyan. How uncertain the whole basis of correlation at this level still is may be seen in Whittington's brief discussion of the Tremadoc series (1954, p. 260).

What has been presented here is a working hypothesis. As far as the writer's knowledge goes, it works. Much more detailed mapping is needed; existing records must be re-examined critically, and pertinent data and doubts must be set forth for debate. There is no short cut to knowledge.

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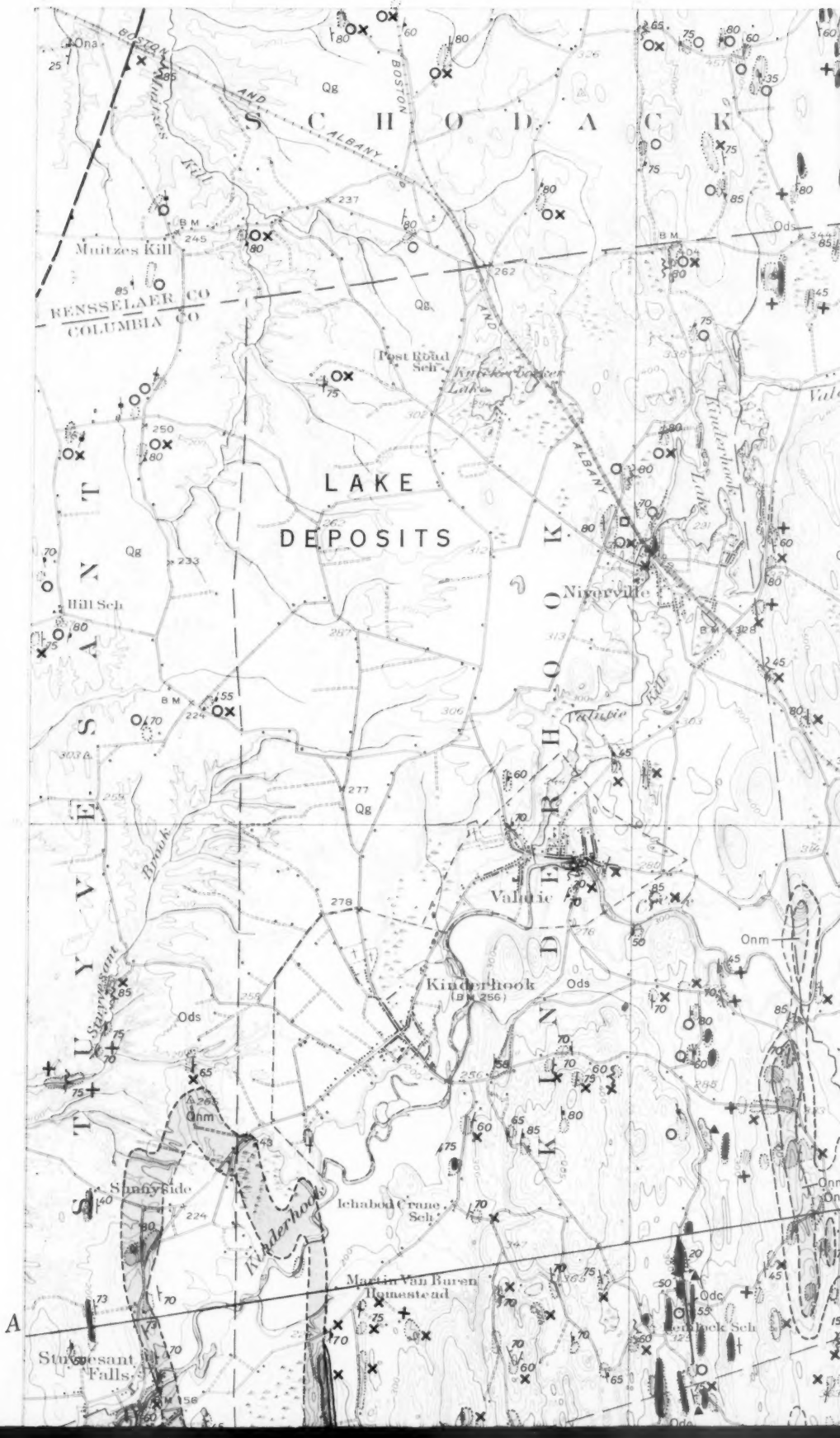
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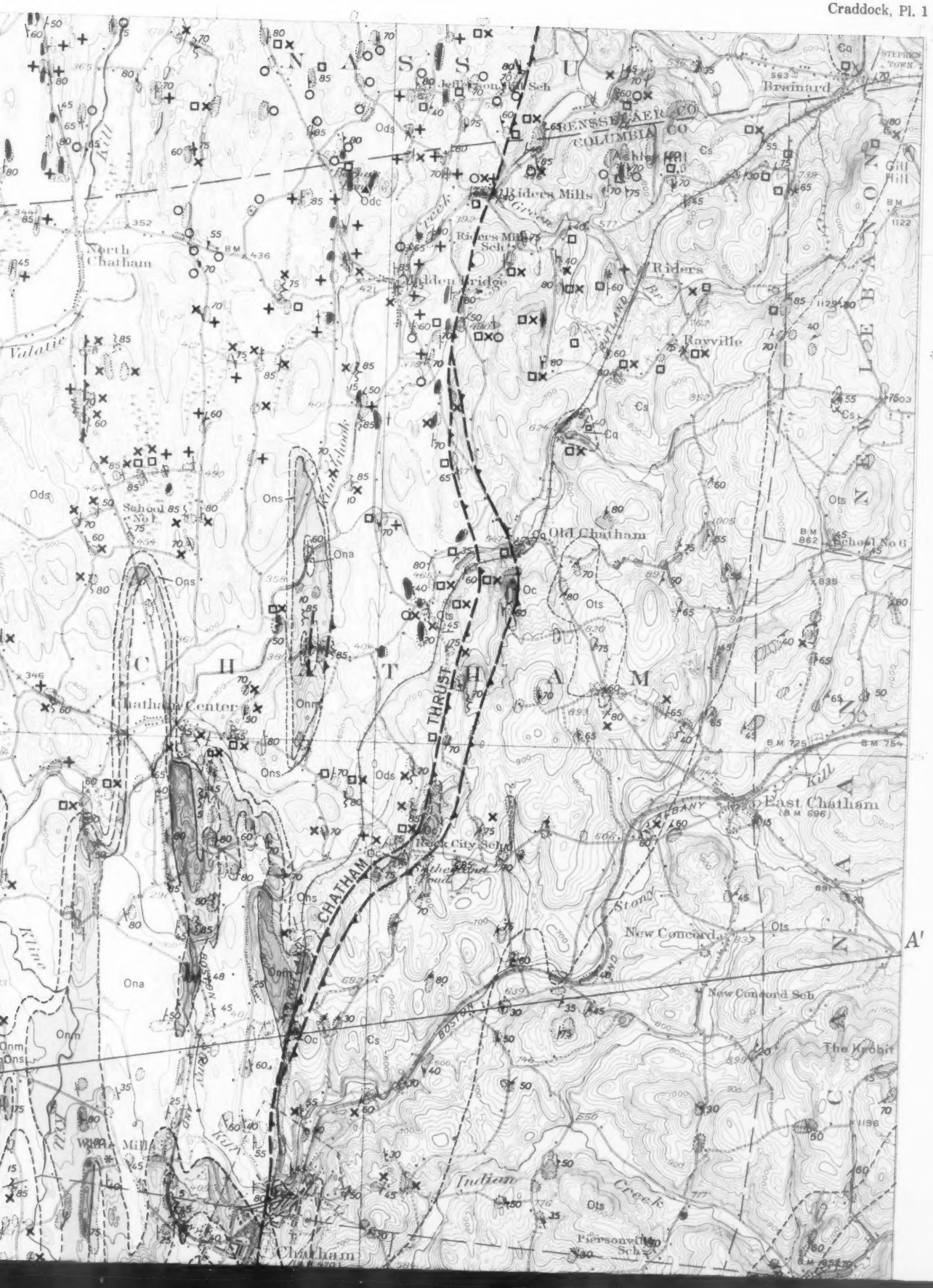
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Kinderhook
Kill
Rail Road
Tributary
Chatham

Craddock, Pl. 1

EXPLANATION

Qg

Deposits of glacial Lake Albany
Distinguished only where they seriously obscure bedrock

QUATERNARY

UNCONFORMITY

SDmc

Manlius—Coeymans limestone

SILURIAN-DEVONIAN

UNCONFORMITY

Trentonian

Ots / Otl

Black slate, Ots; with basal limestone, Otl

UNCONFORMITY

Normanskill

Ona

Austin Glen member
Graywacke with interbedded dark shale

Onm

Mount Merino member
Dark shale with interbedded chert

Ons

Red shale member

Mainly Deepkill

Ods

Green shale
Locally with thin interbedded quartzites

Calcareous sandstone and limestone conglomerate interbedded in the green shale

UNCONFORMITY

Canadian

Oc

Carbonate rock
Massive limestone and dolomite

ORDOVICIAN

UNCONFORMITY

Cq / Cs

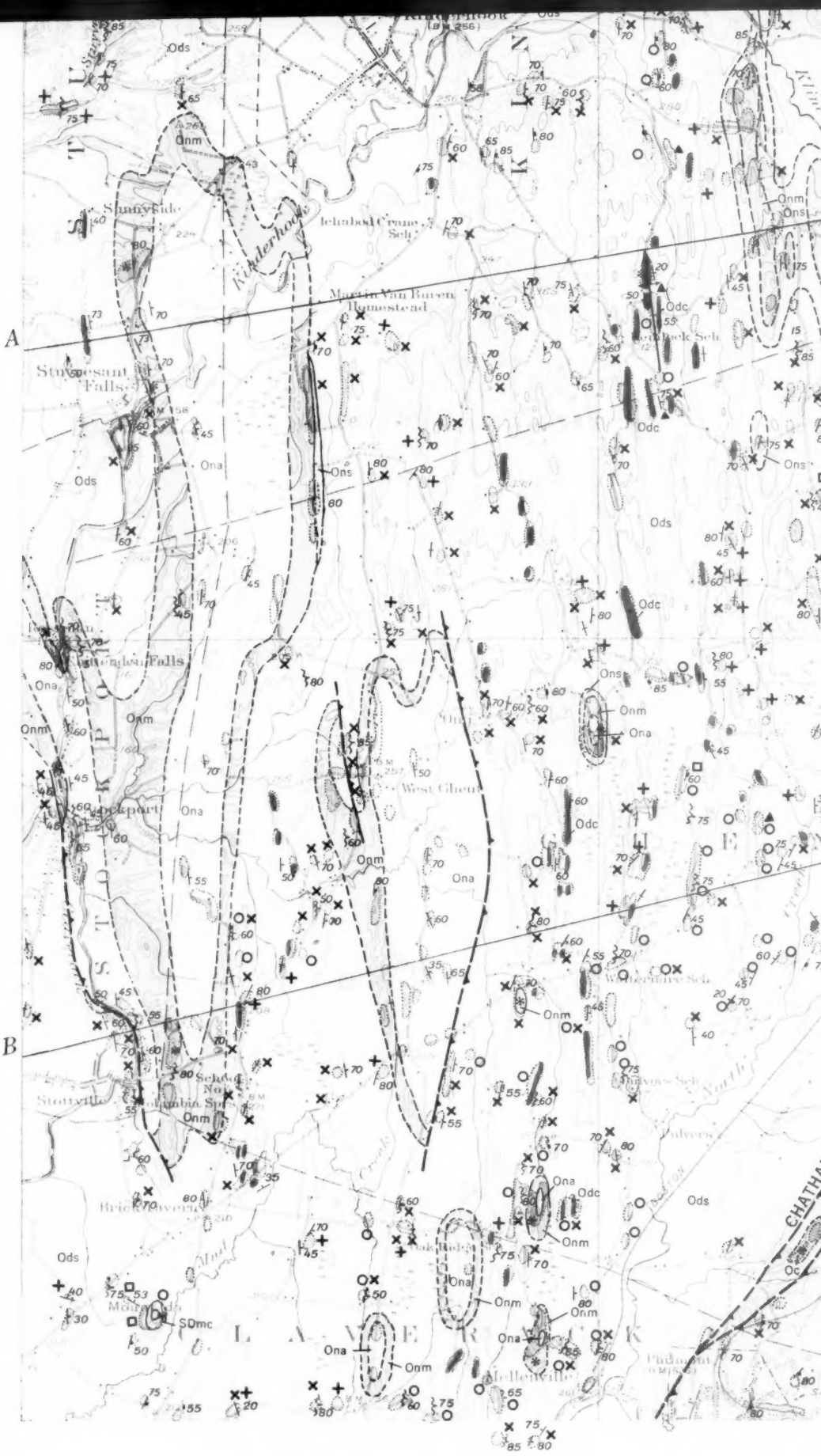
Green slate, Cs; with intercalated graywakes and quartzites, Cq
Locally with calcareous sandstone and limestone conglomerate

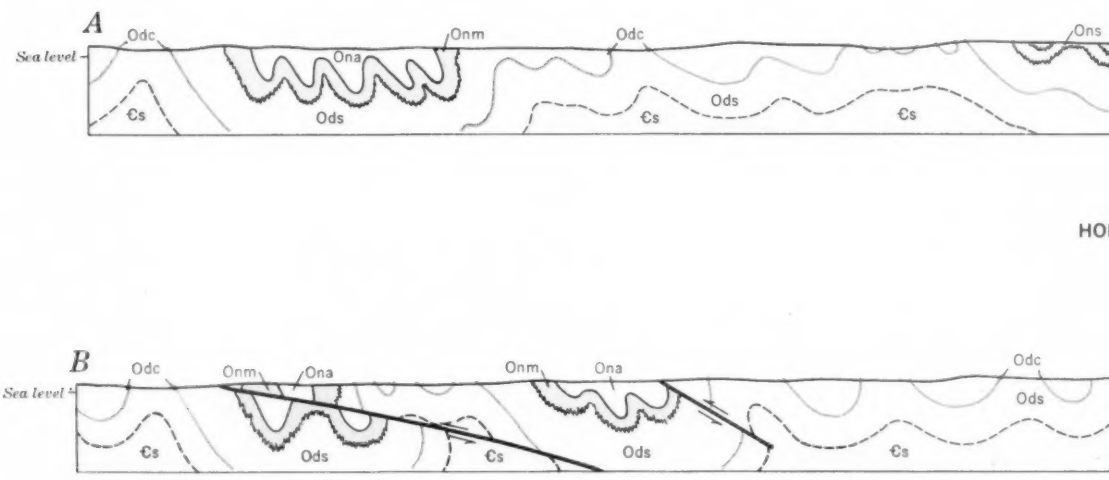
MAINLY LOWER CAMBRIAN

Limit of outcrop

Thrust fault

Normal fault





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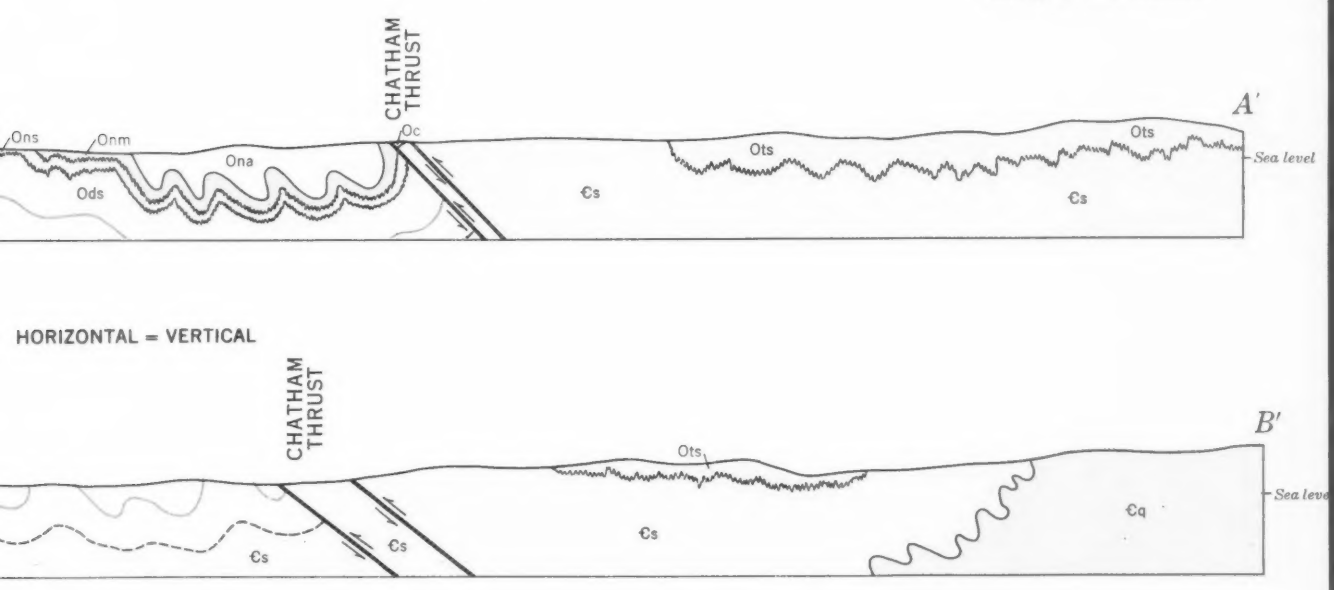
GEOLOGIC MAP AND STRUCTURE SECTION

Co

Geology by J. C. Craddock



IONS OF THE KINDERHOOK QUADRANGLE, NEW YORK

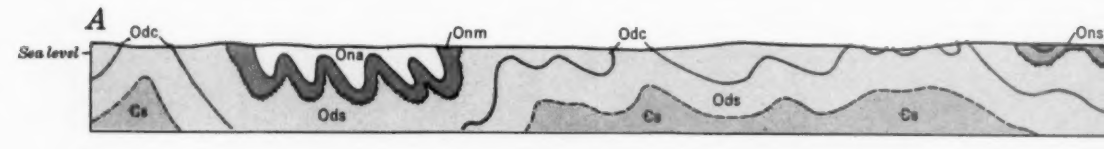
Scale 1/62500

1 2 3 4 Miles

1 2 3 4 5 Kilometers

Contour interval 20 feet.

Datum is mean sea level.



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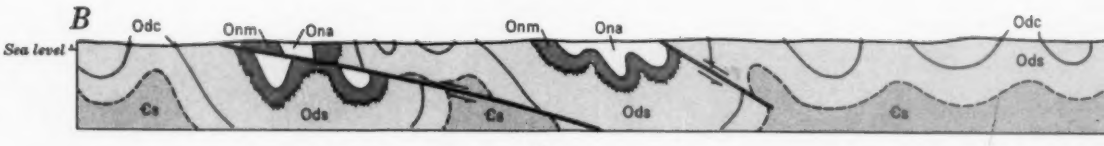

GEOLOGIC MAP AND STRUCTURE SECTION

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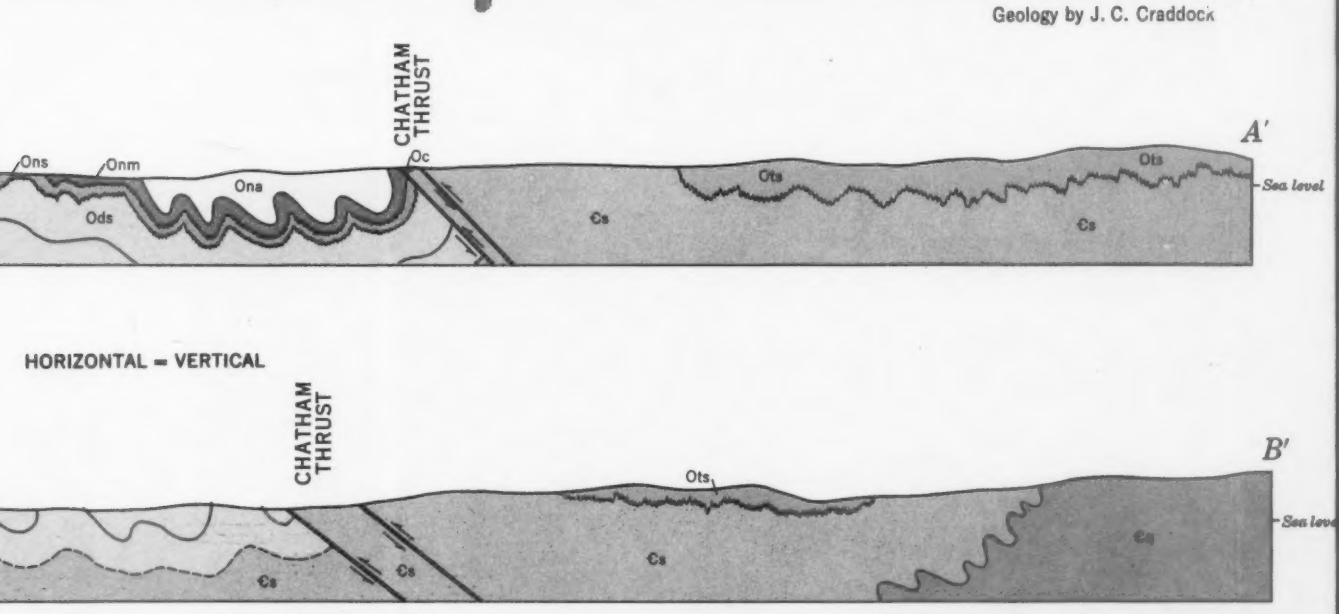
Geology by J. C. Craddock



IONS OF THE KINDERHOOK QUADRANGLE, NEW YORK

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Contour interval 20 feet.

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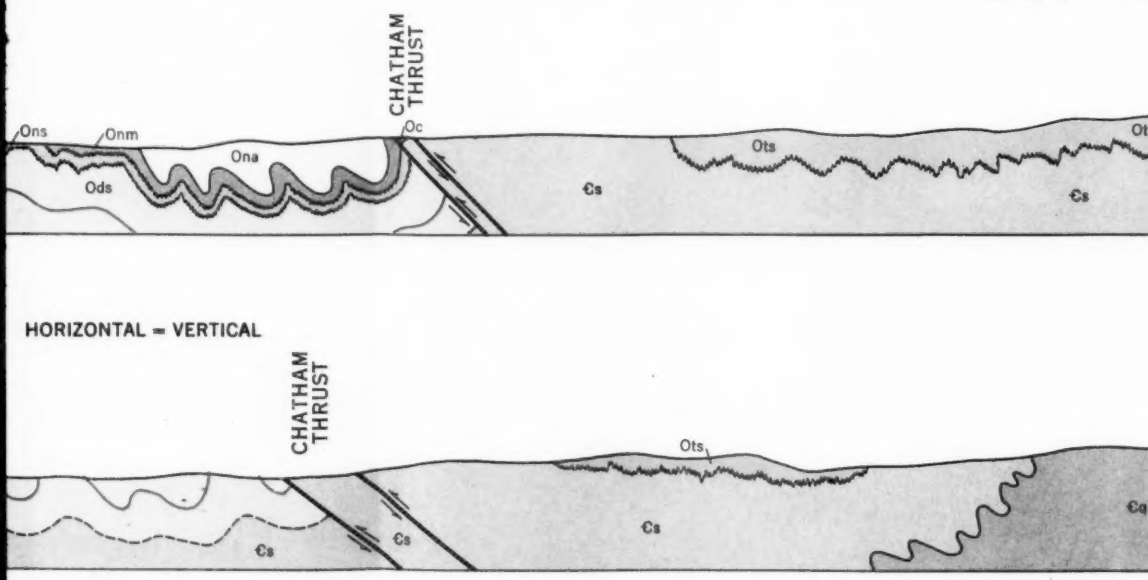

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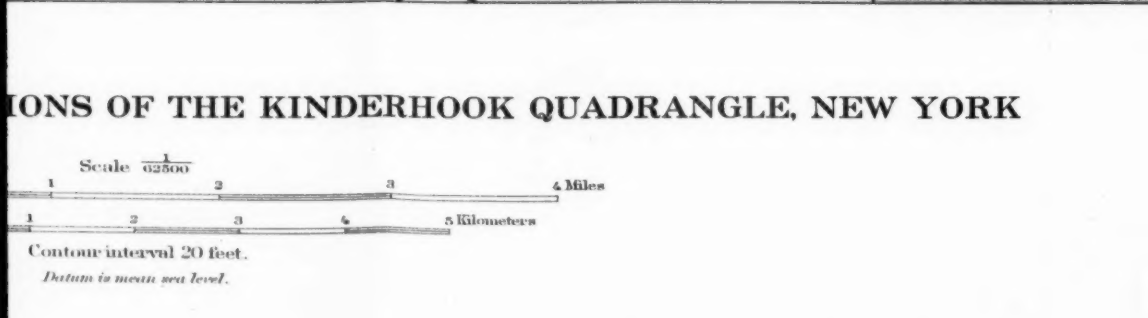

IONS OF THE KINDERHOOK QUADRANGLE, NEW YORK

Scale $\frac{1}{62500}$

1 2 3 4 Miles

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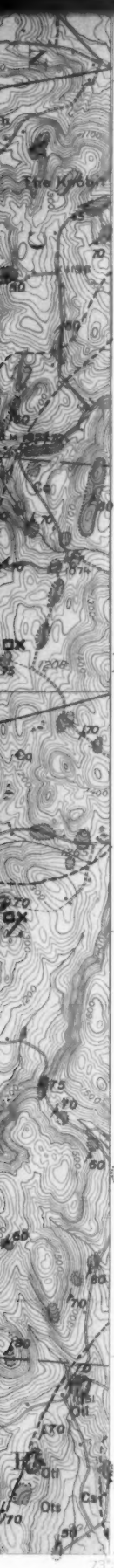
Contour interval 20 feet.

Datum is mean sea level.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BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 68, PP. 675-724, 7 FIGS., 3 PLS. JUNE 1957

STRATIGRAPHY AND STRUCTURE OF THE KINDERHOOK QUADRANGLE, NEW YORK, AND THE "TACONIC KLIPPE"

BY J. CAMPBELL CRADDOCK

ABSTRACT

Detailed mapping of the predominantly argillitic Cambro-Ordovician "Taconic sequence" in the Kinderhook quadrangle, New York, indicates that the Chatham thrust divides these rocks into two distinctive sequences. To the east slates predominate and form a hilly upland, but west of this thrust less resistant shales underlie a gently rolling lowland. Stratigraphically, the eastern sequence is composed of a transgressive black Trentonian (Middle Ordovician) slate, locally with a thin basal limestone, resting upon a thick series of Lower Cambrian green slate, graywacke, quartzite, limestone, and limestone conglomerate (Rensselaer-Nassau-Schodack). Canadian carbonate rocks crop out intermittently along the Chatham thrust, and they are interpreted as slivers trapped during thrusting. The western sequence is primarily Normanskill (Middle Ordovician) and Deepkill (Lower and Middle Ordovician) shale, unconformably underlain by Lower Cambrian shale and overlain by Siluro-Devonian limestone.

Though many small thrusts are present, folding is the principal mode of deformation. The Chatham thrust, however, is a major structural break and continues at least 20 miles southwest of the quadrangle and an unknown distance northward. It is a post-middle Trentonian feature, and maximum displacement is a few miles rather than tens of miles. Unconformities are very important in the geologic history of this area, but some have gone undetected because of the structural complexity and poor exposure. The following formations are believed to have basal unconformities in the Kinderhook quadrangle: the Upper Silurian Manlius limestone, the Trentonian black slate (locally with a basal limestone), the Deepkill shale, and the Canadian carbonate rocks.

Evidence for the existence of the "Taconic klippe" was not found in mapping this quadrangle. Analysis of the development of the klippe hypothesis indicates that it is based principally upon stratigraphic considerations; available structural evidence weighs against this interpretation. While the klippe hypothesis seems to explain well the relations at the north end of the Taconic Range, the problem of adequately defining the boundaries of this "klippe" causes serious doubt about its existence.

An alternative interpretation of the regional relations is suggested, involving unconformities and facies changes in a single indigenous sequence. Trentonian rocks lie unconformably on rocks as old as Precambrian from Vermont to Pennsylvania and pass indiscriminately in and out of the "Taconic klippe." The Normanskill and Deepkill rocks (mainly shale) are interpreted as passing transitionally into limestone to the west; an analogous situation exists in the Middle Ordovician rocks of Virginia. The Deepkill is believed to rest unconformably on rocks of Early Cambrian to middle Canadian age. Middle Canadian formations in the Kinderhook quadrangle are carbonate rocks and appear to rest unconformably upon Lower Cambrian slates; their striking similarity to equivalent rocks in the near-by "autochthonous" series suggests they have not been displaced any great distance. The Lower Cambrian is a thick series of argillite, graywacke, and quartzite with some thin carbonate rocks near the top. The thick, lower part of this series is considered a southward continuation of the Mendon Series of Vermont. The upper strata are interpreted as the offshore equivalents of shallow-water quartzites and carbonate rocks deposited marginal to an eastern welt in later Early Cambrian time.

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Introduction

Nature of the Problem

For many years controversy has existed over the space relations of the major stratigraphic units exposed in the Hudson River valley and the nature of the thrust faults known to be present there. Estimates of the amount of lateral movement along these faults have ranged from hundreds of feet to scores of miles. The present study was undertaken in the hope that detailed work on the structure and stratigraphy of the Kinderhook quadrangle, New York, including the preparation of a geologic map on the scale of 1:62,500, would result in a clearer picture of the nature and relation of these thrust faults to the regional structure and of the stratigraphy of the "Hudson River shale" terrane.

Except for a few scattered references to fossil localities and several reconnaissance surveys, the details of the geology of the Kinderhook quadrangle had been virtually unknown before this study. It seems a curious irony that the quadrangle in which Amos Eaton was born and reared should have to wait some 110 years after his death for a detailed geologic treatment! The few available small-scale maps have represented this area only in general terms. The Geologic Map of New York State (1901) shows the rocks of the quadrangle as "Georgia slate," "Hudson River shale," and "Hudson River metamorphosed." The Geologic Map of the United States (1932) includes Cambrian of the "eastern sequence" and Cambrian and Ordovician of the "Taconic sequence"; Plate I of Guidebook 1, XVI International Geological Congress (1932), makes the same representation. The Geologic Map of North America (1946) distinguishes simply Cambrian and Ordovician. On the Tectonic Map of the United States (1944) the Kinderhook quadrangle lies within a great "klippe," the "Taconic Mountains overthrust sheet," and contains a "window" of the underlying indigenous sequence. This strategic location makes the area an ideal one in which to study this hypothetical "klippe" and the theory of low-angle, far-travelled overthrusts (Fig. 1).

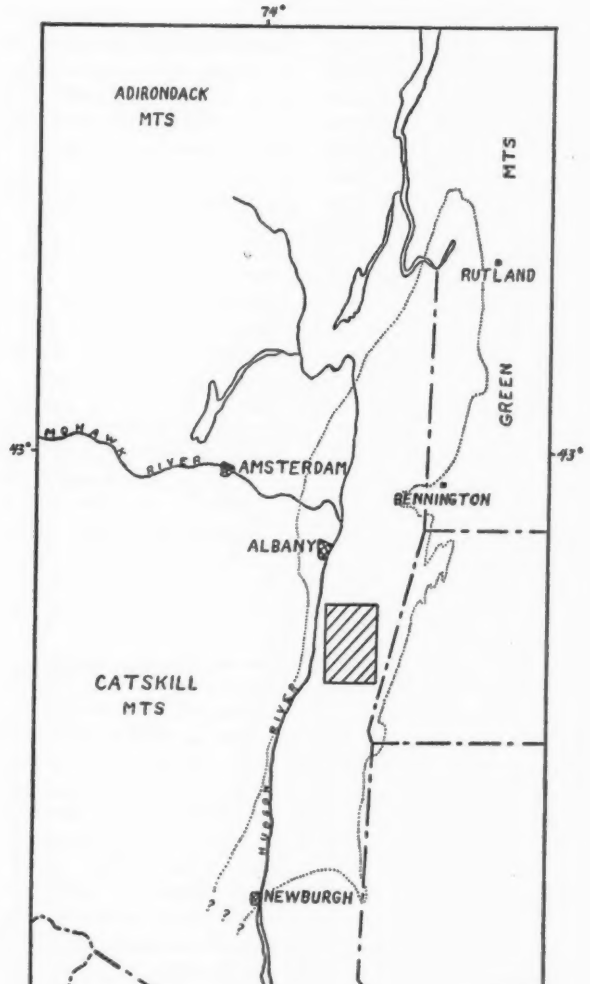

FIGURE 1.—MAP SHOWING LOCATION OF THE KINDERHOOK QUADRANGLE AND APPROXIMATE BORDERS OF THE "TACONIC KLIPPE" (dotted)
Linear distance from Newburgh to Rutland is approximately 155 miles

Other reasons, however, dictate the selection of this area as a critical one in the solution of these problems. The five adjacent quadrangles to the north, northwest, west, southwest, and south have all been mapped, but interpretation has been severely hampered by the lack of

detailed information from the Kinderhook quadrangle. Moreover, this quadrangle offers a unique opportunity for studying all the major stratigraphic units of the "Taconic sequence". The northern margin of the area is bordered by the "Lower Cambrian" shales described by Ruedemann (1930, p. 73–85) in the Capital district. Along the southern border are the unconformable black Trentonian slatee found by Weaver (1953, Ph.D. thesis, Univ. of London) in the Copake quadrangle. In the central and western portions of the quadrangle, the graptolite-bearing Ordovician shales (which are present in the quadrangles to the west and southwest but apparently lacking just to the south) crop out over large areas. One erosional remnant of Silurian and Devonian limestone, resting unconformably on the older folded shales, is present in the southwest rectangle—not far from the classic outlier at Becraft Mountain. Clearly this quadrangle offers an excellent opportunity for the study of these various units and their relations to one another.

Field Work

Seven months was spent in the field during the summer of 1952 and the summer and fall of 1953. Field mapping was executed on × 2 photostatic enlargements of the U. S. Geological Survey 15-minute Kinderhook, New York, quadrangle map.

The results of these field studies are incorporated in Plate 1. In addition to the outcrop pattern of the various stratigraphic units, the map includes representative readings of dip and strike and other structural data. Fossil localities, both those mentioned in the literature and those found by the writer, are indicated. It seemed advisable in this area of poor exposure and confusing relations to also include an outcrop map for the reader's critical evaluation.

In referring to specific localities in the text, the writer has adopted a modification of the system for locating points introduced by John L. Rich (1921, p. 479–81). The quadrangle is divided into the nine 5-minute rectangles, each of which is named with respect to its compass direction from the center of the quadrangle, *i.e.* NW (northwest), N, NE, W, C (center), E, etc. Within a rectangle a given point is located by its N-S and E-W co-ordinates, expressed as distance in tenths of an inch from the border of the rectangle. For example, the location (C13S17E) would signify a point in the center rectangle, 1.3 inches south of the north border and 1.7 inches east of the west border. All outcrops were located with this system while in the field, and the reader should be able to locate described exposures easily.

Previous Work

Studies of the Hudson River valley strata began in the early days of American geology, and a bibliography of the region includes the names of some of history's most able geologists. Amos Eaton, born in the town of Chatham, prepared a section from the Catskill Mountains to the Atlantic Ocean as early as 1818—a feat which few geologists today would care to undertake! Two years later Chester Dewey sketched a section from Troy, New York, to Williamstown, Massachusetts; in his text he refers to the "graywacke-slate" in Chatham. In 1835 the New York Geological Survey was established, with W. W. Mather, Ebenezer Emmons, Lardner Vanuxem, and James Hall in charge of the four geological districts. Six years later the monumental *Geology of New York* appeared, and in his discussion of the 1st district Mather (1842, p. 385) mentions exposures of the "Hudson-river group" in Kinderhook Creek from Valatie to its mouth. Emmons (1842, p. 135–164) in the same publication proposed his "Taconic System" to include all the beds from the Primary (Precambrian) in the Hoosac ranges to the east up to the New York Transition System (Potsdam and above) on the west; for the next fifty years most of the literature on the region was devoted to discussion of this proposal and gave rise to the "Taconic controversy" of the last century. The matter was settled when Dana (1877; 1886a; 1886b; 1890) and Walcott (1888) announced the discovery of "Lower Silurian" (Ordovician) fossils in limestone of the "Taconic System." This early "Taconic controversy" was primarily concerned with the relative ages of large stratigraphic units and is not directly related to the problem of the "Taconic klippe", though of course the results of these early studies have been the foundation for all subsequent investigations.

While considerable literature exists on the broader Hudson-Taconic region, little is available on the Kinderhook quadrangle. S. W. Ford (1871; 1873; 1878) described the "Primordial" rocks at Troy and Schodack Landing, just northwest and west respectively of the Kinderhook quadrangle, and established the presence of the Lower Cambrian along the east bank of the Hudson River. I. P. Bishop (1886; 1890) listed several fossil localities and noted limestone belts trending through a predominantly shaly terrane. Dale (1893; 1904) covered the northeast corner of the quadrangle in the course of his regional studies; he described and separated the stratigraphic units in detail, but mapped only the larger divisions. Ruedemann and Wilson (1936, p. 1537) published a rough map of the Deepkill and Normanskill chert outcrop areas. Goldring (1943, Map 2) gives a reconnaissance map of the western margin of the Kinderhook quadrangle. During his investigation of the Rensselaer graywacke Balk (1953) studied and mapped portions of the northeastern quarter of the quadrangle.

Acknowledgments

The writer is pleased to express his gratitude to the many who have assisted him during this investigation. Prof. Walter H. Bucher first interested the writer in the problem; his experience and his enthusiasm have aided immeasurably throughout this study. Prof. Marshall Kay has most generously shared his broad experience in the Taconic region and has verified the identifications of fossils. Dr. Winifred Goldring of the New York State Museum helped the writer greatly at the beginning of his field work and continued to do so until its completion; she also kindly rendered a valued opinion on certain paleontological problems. Prof. John D. Weaver guided the writer to critical exposures in the area and freely shared his experience in the region.

Prof. John Imbrie identified some of the fossils and suggested recovery techniques that made possible generic identification of originally obscure specimens. Dr. Donald W. Fisher of the New York State Museum graciously made available unpublished results of recent studies and aided in assigning an age to the carbonate rock exposures. The writer has benefited from discussions with Dr. Albert Bally, who has studied similar problems in the Swiss Alps. Dr. Rousseau Flower identified cephalopod specimens and gave valuable advice on correlation problems. Prof. Roger Batten identified gastropod specimens and helped in the preparation of thin sections of other fossils. Dr. Christina L. Balk kindly examined material from Ashley Hill and identified the Lower Cambrian faunule. Prof. Henry S. Sharp guided the writer to important exposures in and around Stuyvesant Falls.

Discussion with and assistance from fellow students is sincerely appreciated, especially that of W. C. Kelly, R. A. Barker, Hubert Gabrielse, John MacFadyen, Robert Duschatko, and Leonard Larsen. The writer thanks the many kind people of Chatham, New York, who assisted in so many ways during the field seasons. The New York State Museum and the Department of Geology, Columbia University, helped defray field expenses. The assistance of Dorothy Craddock in the preparation of maps and manuscript was invaluable. A grant from the General Research Fund of the Graduate School of the University of Minnesota paid part of the drafting expense.

Sincere thanks is offered the following for critically reading the manuscript: Professors Walter H. Bucher, Marshall Kay, and Charles H. Behre, Jr., of Columbia University; John Rodgers of Yale University; Marland P. Billings of Harvard University; and Dr. Donald W. Fisher of the New York State Museum. The writer alone, however, must accept responsibility for the conclusions reached in this paper.

Regional Setting

The valley of the Hudson River and its northward continuation, the Champlain valley, form a conspicuous linear lowland that extends from the region of Newburgh, New York, north to the international boundary. South of Newburgh the lowland swings southwest through New Jersey and Pennsylvania into the Great Valley of the Appalachians. In New York this depression is bounded on the west by scarps of the Catskill Mountains in the south and by the Adirondacks in the north, and the two mountain areas are separated in the latitude of Albany by the valley of the Mohawk River.

Eastward from this lowland the slopes rise gently through a belt of foothills to the peaks of the Green Mountains in Vermont. South of the Green Mountains this eastern highland extends through the Hoosac Range of Massachusetts and the Housatonic Highlands of Connecticut; at this latitude it swings gradually southwest and becomes the Hudson Highlands. This upland crosses the Hudson River just below Newburgh and continues southward, with a brief disappearance in Pennsylvania, into the Blue Ridge of the Appalachian Mountains. However, from the latitude of Brandon, Vermont, southward to the Housatonic Highlands this gentle eastward rise in elevation is abruptly interrupted by the Taconic Range—sharply defined to the north, but fading out against the Highlands to the south.

Physiographically the Kinderhook quadrangle may be conveniently divided into four sectors. In the extreme southeast corner the surface drops off into the conspicuous lowland that parallels the western edge of the Taconic Range. Most of the eastern and southeastern portions of the quadrangle, however, constitutes a belt of rolling foothills, ranging up to 600 feet in elevation. A large area of low relief at an elevation of 200–300 feet in the northwestern quarter of the quadrangle represents the southern extension of glacial Lake Albany. The remainder of the quadrangle is a gently rolling lowland that descends westward to elevations below 100 feet near the Hudson River.

The problem of the "Taconic klippe" involves chiefly Cambrian (including all beds down to the basement complex) and Ordovician sedimentary and metasedimentary rocks. These rocks underlie the entire Champlain-Hudson lowland and extend southward in the Great Valley. In the north they continue westward in the Mohawk Valley and along the north flank of the Adirondacks, almost uniting again in Ontario to enclose the Precambrian core of the mountains. Eastward they extend to the Precambrian complex of the Green Mountain-Hudson Highland range. Highly metamorphosed Cambro-Ordovician rocks are present east of this range, but their relations and correlation are obscure. In western Connecticut Cambro-Ordovician Stockbridge limestone and Berkshire schist occur in a northeast-trending belt about 15 miles wide. To the east lie highly metamorphosed gneisses and schists, generally called Precambrian, which are eventually truncated by the Connecticut Triassic basin (Gregory and Robinson, 1906). Emerson (1916, Pl. X) shows an eastward progression in Massachusetts from the Precambrian through Ordovician, Silurian, and Devonian metamorphic rocks to the Triassic basin, and thence through Carboniferous beds into the Boston basin. In Vermont a thick Cambro-Ordovician sequence east of the Green Mountains is succeeded by Silurian and Devonian in New Hampshire (Thompson, 1952, p. 17–19; Billings, 1952, p. 23–24).

In summary, Cambro-Ordovician rocks are exposed primarily in a linear belt (Fig. 2) averaging 20–25 miles across and extending from Canada into Pennsylvania and beyond. Rocks in the eastern margin of this belt are highly metamorphosed, and relations here and east of the Precambrian upland become obscure. Much of the Cambro-Ordovician belt is at least slightly metamorphosed, but most of it is still amenable to stratigraphic analysis. Fossils are not abundant but help to establish the general stratigraphic relations; large areas, however, have not yet been studied in detail. West of this belt lie the classical sections of the Mohawk Valley and northwestern New York, which are highly fossiliferous and have been carefully studied. Thus from east to west metamorphic grade decreases, and the structural and stratigraphic relations are better known.

A number of factors combine to make this region a distressing one for detailed investigation. Most of the quadrangle is underlain by shale or slate, and outcrops are poor and scattered—a condition aggravated still further by the ubiquitous glacial debris. The general scarcity of fossils forces correlation on the basis of lithology and stratigraphic position, a procedure complicated by the fact that many of the Lower Cambrian lithologies are repeated in the Ordovician—and in approximately the same sequence! Accordingly these deformed rocks must be traced along the strike from one outcrop to the next; but even this becomes difficult because of the complexities of deformation.

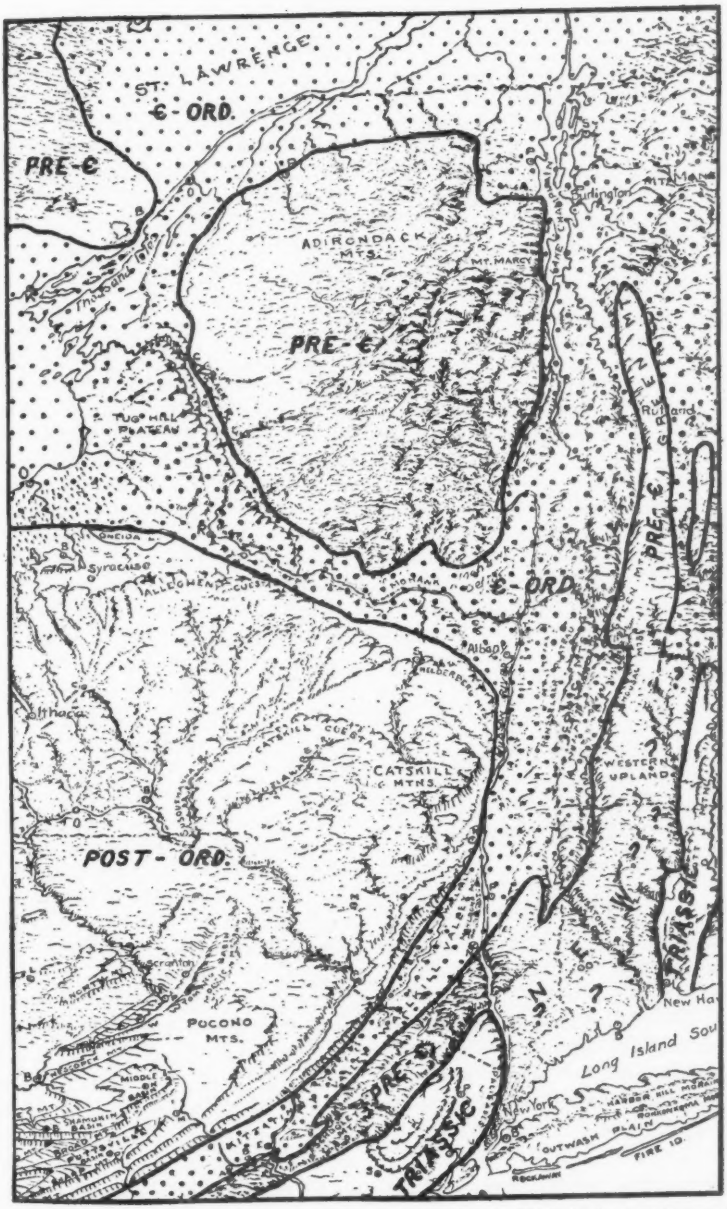

FIGURE 2.—MAP SHOWING REGIONAL PHYSIOGRAPHY (by A. K. Lobeck) AND GENERAL GEOLOGIC RELATIONS

Stratigraphy

Introduction

The Chatham thrust divides the exposed bedrock of the quadrangle into two provinces,

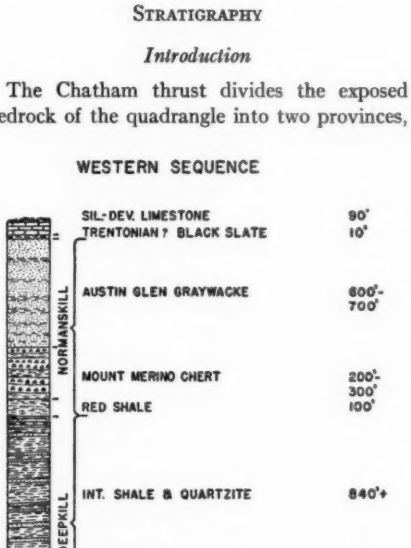

FIGURE 3.—COLUMNAR SECTION OF ROCKS WEST OF THE CHATHAM THRUST

essentially equal in area but distinct from each other topographically, metamorphically, and stratigraphically. It is logical therefore to divide the discussion of the stratigraphy into two sections.

For each of the two provinces a general discussion of the stratigraphy will be followed by a detailed description of the terranes and their units. Each of these units will be treated in terms of its description, typical exposure, distribution, thickness, evidence of stratigraphic position, fauna, and correlation. As these rocks cannot in most cases be established as formations by accepted stratigraphic procedures, related rock units have been described together as "terranes."

The terminology applied to sedimentary layer thickness follows Krumbein and Sloss (1951, p. 97); textural terms are after Wentworth (1922, p. 381). Wherever possible, color nomenclature is taken from the National Research Council Rock-color Chart (1948).

Sequence West of the Chatham Thrust

General description.—This sequence is composed principally of shales and sandstones and is considered to be younger, in the main, than most of the sequence to the east (Fig. 3). The western sequence forms a gently rolling, drift-covered lowland whose main features are nevertheless determined by the lithology of the bedrock. This relationship is well illustrated on the outcrop map (Pl. 1) by the resistant limestone conglomerates that form the ridges and the soft shales that underlie the intervening valleys. The strata have been universally folded, but in general deformation has not been severe. Massive competent beds show broad gentle folds, but the shales in places are strongly contorted. Metamorphism is of a low grade; some of the shales develop a good cleavage and might be classed as slates. Graptolites are abundant in the Normanskill shales, but the older shales seem barren of fossils.

Green shale terrane.—Of the terranes in the western sequence the green shale terrane occupies the largest area and is by far the most confusing. This terrane is composed of a thick sequence of green shales; the lithologies are so uniform throughout that the stratigraphic position of a given outcrop can seldom be determined on lithologic characteristics alone. Fortunately, however, a few distinctive beds are present in the terrane, and by tracing these key beds the structure and stratigraphic sequence can be established.

The following description of the rock units within this terrane begins with the oldest unit.

OLIVE ARGILLITE UNIT: At typical exposures this unit is a fissile, fine-grained, soft olive argillite. It is easily scratched with a knife and is unaffected by dilute hydrochloric acid. Locally it coarsens almost to a silt and assumes a shaly or a crumbly aspect. It is usually a distinct olive but in places grades into zones of grayish green, red, and rarely dark gray. It weathers reddish-brown or purplish though the coarser varieties tend to retain the olive color; weathering buries the outcrop in a talus of thin chips, or elongate prisms where both bedding and cleavage are well developed. Local intense deformation in some places is accompanied by white quartz veins. Interbedded 1- to 2-inch

greenish quartzites are not uncommon, and these beds are strikingly similar to higher horizons in this terrane.

Typical exposures can be observed in the vicinity of the Hemlock School (C25N4E) or at the intersection of the county roads 1 mile north of Kinderhook Lake (N17S3E).

Owing to the poor and scattered outcrops and the uncertainty of the stratigraphic sequence of the variations within the unit, no accurate measurement of thickness is possible. It is probably at least several hundred feet thick.

This unit crops out conspicuously in the north, northwest, and south, but is present only in scattered exposures in the center of the terrane (Pl. 1).

The evidence of the low stratigraphic position of this unit is twofold. In the vicinity of the Hemlock School (C25N4E) the olive argillite definitely underlies the calcareous sandstone-limestone conglomerate horizon. The outcrop pattern of these beds with respect to the conglomerates and the Normanskill synclines corroborates this interpretation.

The only organic remains found in this unit in the Kinderhook quadrangle are some sinuous trails about a quarter of an inch wide. They are smooth and shallow and suggest worm trails.

Flower (1953, personal communication to Professor W. H. Bucher) reports *Didymograptus* sp., *Phyllograptus* sp., and *Tetragraptus* sp. from a road cut in silty olive shale on U. S. Route 9, 1½ miles south of Cherry Hill in the Catskill quadrangle (NE21N14W). The writer collected *Didymograptus* sp. from this locality. The lithology is similar to the silty varieties of the olive argillite in the Kinderhook quadrangle. On the basis of this fauna the writer tentatively correlates the olive argillite with the lower Deepkill shale. Some of it may be older.

BLACK CHERT UNIT: This unit is very similar to the black cherts in the higher Normanskill beds. The cherts occur in 1- to 2-inch beds interstratified with black fissile shales; they are everywhere folded, in places intensely, owing to their stratigraphic position immediately below a massive competent unit. Though mainly black, some greenish beds are usually found as well. Microscopically the chert appears as a cryptocrystalline aggregate; thin laminae of quartz grains and occasional rounded iron-oxide grains suggest a detrital origin. Fractures crosscut the rock, and microscopic quartz veins are common.

The best exposure of this unit is in the core of the Hemlock School anticline (C25N4E). It is present in the quadrangle only at a few scattered outcrops along this anticlinal trend and on the west side of Bachus Pond (N13S2W). It appears to be less than 20 feet thick; it rests on olive argillite and is overlain by the calcareous sandstone-limestone conglomerate unit.

As mentioned, this lithology is indistinguishable from the graptolite-bearing Normanskill cherts. Collecting in the latter unit almost always yields graptolite fragments within a few minutes, but the former seems barren of fossils even with the most patient searching.

Since this unit lies above beds believed to be Deepkill and since bedded cherts are unknown below the Deepkill in the region, this unit is also tentatively correlated with the Deepkill shale.

CALCAREOUS SANDSTONE WITH LIMESTONE CONGLOMERATES: These two lithologies are described together because they form a distinctive unit in which the two rock types succeed each other at random both vertically and laterally. The calcareous sandstone ranges from a bluish gray to light tan on a fresh surface, but weathers rust color or moderate brown. The rock is mainly medium to coarse, rounded quartz grains in a matrix of calcium carbonate. Extensive weathering dissolves the carbonate cement, and the rock becomes a porous, friable sandstone. The earlier stages of weathering carve the rock into exotic rounded shapes and produce a surface of rounded quartz grains. Pebbles of black chert are locally present, probably derived from the unit below. In almost all outcrops this rock contains a scattering of distinctive, minute, bright orange-colored flakes on the fresh surface; X-ray data show them to be calcite, apparently with limonitic stains. Within this quadrangle these orange flakes have proven useful in separating this Ordovician unit from a similar lithology of Early Cambrian age.

Microscopic examination shows that most of the minerals are rounded or subrounded and that the rock is poorly sorted. Though composed mainly of quartz and calcite, the sand-

stone also contains small amounts of well-rounded zircon, plagioclase, microcline, detrital oölite, rounded siltstone fragments, tourmaline, rounded iron-oxide grains, and in one section a small shell fragment (possibly of a punctate brachiopod).

The conglomerate contains limestone fragments ranging from pebbles to boulders. These fragments are generally rounded and have a tendency toward flatness; an average fragment has dimensions on the order of half an inch by 2 inches by 3 inches. Most limestone fragments are medium gray and very fine-grained, but fragments of calcareous sandstone are not uncommon. The matrix contains abundant rounded quartz grains, some black chert fragments, and orange-colored limonitic spots as in the calcareous sandstone. While the flat pebbles are subparallel in some outcrops, most localities are characterized by heterogeneity of fragment orientation. It is difficult to avoid the impression of rapid deposition from swift currents. On a fresh surface the matrix and pebbles are both medium gray, but the pebbles weather light gray and contrast sharply with the matrix both in color and texture. Weathering in places brings out fine laminations in some of the pebbles, but most surfaces are smooth; "pitted" pebbles are not found.

The best exposures are found in the Hemlock School anticline (C25N4E) and along the dirt roads to the east, south, and north.

The maximum observed thickness of 135 feet is on the east limb of the Hemlock School anticline. Elsewhere sections of 20 feet, 22 feet, 25 feet, 30 feet, 50 feet, 55 feet, and 80 feet have been measured; in most cases these figures probably do not represent the entire thickness of the unit.

Outcrops of this unit are scattered almost throughout the green shales of the western sequence; because of their uniformity of lithology and relatively great thickness, the writer believes these scattered exposures may be assigned to the same stratigraphic zone. This assumption is further supported by the alignment of these outcrops on the map and by the uniformity of the associated lithologies.

The evidence for the stratigraphic position of this unit rests largely on its outcrop pattern with respect to the other units of the western sequence. At the Hemlock School anticline (C25N4E) it overlies the olive argillite and black chert units. These linear belts of outcrop are in most cases a certain distance from the Normanskill areas and give the definite impression of "wrapping around" these synclinal remnants. Generally the interbedded shale and limestone unit lies between the base of the Normanskill and the limestone conglomerate horizon, though this relation may be locally obscured by deformation.

The only fossil the writer found in this unit is a dendroid graptolite from a pebble of calcareous sandstone in the conglomerate of the Hemlock School anticline.

However, at an outcrop on U. S. Route 9, three-quarters of a mile southeast of Cherry Hill in the Catskill quadrangle (NW23N15W), just southwest of the Kinderhook quadrangle, Clinton Kilfoyle and later Flower (1953, personal communication to Professor W. H. Bucher) reportedly fround *Triograptus* sp. and some poorly preserved dendroids. These beds are mainly an alternating sequence of black shales and 1- to 2-inch limestone beds; several interbeds of limestone conglomerate up to a few feet thick are present. This outcrop was mapped originally by Ruedemann (1942a) as Schodack, but since the discovery of the graptolites it has been considered Deepkill (Goldring, personal communication).

While these conglomerates are considerably thinner than the unit under consideration, the gross aspect of the beds southeast of Cherry Hill is strikingly similar to the calcareous sandstone-limestone conglomerate unit and the interbedded shale and limestone unit to be described next. Because of this similarity to known Deepkill beds, the presence of black chert pebbles, the discovery of a dendroid graptolite in a pebble, and its stratigraphic position above beds believed to be Deepkill, the calcareous sandstone-limestone conglomerate unit is also correlated with the Deepkill shale (Pl. 2, fig. 1).

INTERBEDDED SHALE AND LIMESTONE UNIT.—The shale is an exceedingly fine-grained, slightly micaceous, fissile black argillite. Bedding-plane surfaces are very smooth in marked contrast to the "gritty" black shales with graptolites in the Normanskill. At a few exposures green shales are also found in this unit.

Interbedded with these black shales in regu

lar alternation is a series of thin limestone beds. Most of these limestones are 2–4 inches thick, but range from half an inch to 30 inches. On a fresh surface they are bluish-gray or medium gray, but weather to light gray. Many of the limestones are very siliceous and tend to break with a conchoidal fracture; some of the weathered sandier limestones show distinct cross-bedding.

In addition to interbeds of limestone, other lithologies are present, though less conspicuous. Quartzite interbeds, up to 12 inches thick, also occur. More common are beds of limestone conglomerate, usually 1–10 feet thick and consisting of heterogeneous limestone pebbles in a calcareous sandy matrix. Fragments of earlier limestone pebble conglomerates are present though rare. Flaggy black cherts occur in the sequence in a few exposures.

Excellent exposures are found on the county road 1 mile west of Malden Bridge (N23S9W) and in the bed of the Kline Kill east of the bridge at Ghent (S1S15W). This latter locality shows four separate conglomerate horizons—18 inches, 2 feet, 4 feet, and 10 feet thick respectively.

The thickness of this unit is difficult to determine as it is folded and faulted where best exposed. It is believed to be about 100 feet thick.

The interbedded shale and limestone crops out in close conjunction with the calcareous sandstone-limestone conglomerate unit (Pl. 1), and it might be better to map the two units as one since the number of outcrops is limited. Both units are conspicuously absent east of the Chatham thrust.

On Kinderhook Creek below a bridge foundation 1 mile south of Malden Bridge (N27N2W), both the calcareous sandstone-limestone conglomerate unit and the shale and limestone unit are exposed; the latter overlies the former. In the bed of Kinderhook Creek at Stuyvesant Falls, the sequence from the shale and limestone unit up to the Normanskill beds is continuously exposed, though interrupted by a small thrust. From these exposures and the map pattern this unit can be assigned a stratigraphic position.

No fossils have been found in this unit in the Kinderhook quadrangle, but it is lithologically identical to the road cut three-quarters of a mile southeast of Cherry Hill in the Catskill quadrangle (NW23N15W) that is considered Deepkill. On the basis of this correlation and the presence of bedded cherts this unit is correlated with the Deepkill shale.

INTERBEDDED SHALE AND QUARTZITE UNIT: This unit is a thick sequence of shales, generally greenish, with interbedded thin quartzites. The rock is fissile to shaly, fine-grained, soft, and unaffected by acid. Some zones contain considerable detrital quartz and under stress may become silicified to a fine-grained quartzite as noted by Ruedemann and Wilson (1936, p. 1542) at Stuyvesant Falls. The bulk of the shale is a grayish green that weathers dirty gray. Toward the top of the unit is a definite zone of predominantly red shale, though green and black shales are also present in lesser quantities. This zone is well developed in the eastern part of the western sequence, but it seems to be absent to the west.

Interbedded throughout these shales are numerous thin quartzites, the two lithologies occurring in regular alternation. These quartzites are generally fine-grained, and many specimens show cross-bedding and fine laminations. Most commonly they are greenish, but some are brown, gray, and bluish gray. They range from half an inch to 8 feet thick, but as a rule they are 1–2 inches thick; some of the thicker beds seem to be lenses and pinch out along the strike. Commonly they break with a subconchoidal fracture, and the broken surface has a dull waxy luster. The quartzites weather light gray and form miniature ridges separated by valleys of soft shale. Small pockets of manganese oxide are present locally, and a dendrite pattern can be observed in places. Poorly developed ripple marks have been found at a few outcrops on the bedding surfaces. Thin beds of greenish chert and bluish-gray limestone also occur scattered through the shale.

Microscopically the quartzite is composed mainly of subangular fine-grained quartz with interbedded argillaceous laminae. Traces of garnet, zircon, iron oxide, and feldspar are also present, and most of these grains are somewhat rounded.

By far the best exposure of this unit is in the bed of Kinderhook Creek at Stuyvesant Falls (W17N9E); the section here extends from the falls upstream to the dam, where overlying Normanskill beds are exposed. Another excellent outcrop is in the road cut a quarter of a

mile south of the Kinderhook road on U. S. Route 9H (W21S11W).

The approximate thickness of these beds can be determined at the Stuyvesant Falls exposure. In this section the dip steepens upstream and up section, but folding is not apparent if present. Assuming no repetition by folding and 65° as a reasonable value for the average dip, calculation yields a figure of about 840 feet for the thickness from the thrust fault in the falls up to the Normanskill beds in the dam.

No attempt has been made to map separately the rocks of this unit and those of the olive argillite unit. While the two units are clearly distinguishable in their typical exposures, all transitions between these end members exist, and at many outcrops it is impossible to assign the rock to one unit or the other. These two units comprise the bulk of the green shale terrane, and attempts to unravel the structure and stratigraphy would be practically futile were it not for other key units. The interbedded shale and quartzite unit herein described is confined to the margins of the Normanskill synclinal remnants, but assignment of stratigraphic position to rocks of a given outcrop is complicated by the recurrence of identical lithologies both in the olive argillite unit and in the true Lower Cambrian elsewhere in the quadrangle.

Fossils are as scarce in this unit as in those beneath it. In the upper red shale zone many of the thin quartzites show low sinuous ridges on their undersurfaces, probably the molds of tracks on the shale surface, produced by the deposition of silt. The only other organic feature observed by the writer is a problematic impression in the Stuyvesant Falls section. About 125 feet north of the bridge on the west bank, the steeply dipping bedding surfaces reveal several large radiating structures (Pl. 3, fig. 1). They consist of a series of grooves, semicircular in cross section and a quarter of an inch wide, radiating outward from an indistinct central area. The entire structure is roughly circular and measures about 2 feet across. Bucher has suggested that they may represent feeding trails of sessile worms, similar to those found at the present time on the north German tidal flats. Somewhat comparable occurrences are illustrated by Abel (1935, Figs. 258–260, p. 289; Figs. 324–328, p. 388–392).

In two remaining areas Walcott (1912, p. 189, 193, 200) collected fossils of early Cambrian age; one area is near the north boundary of the map, the other along the western edge of the quadrangle toward the south.

The first area contains the following localities and fossils (Walcott's locality numbers):

No. 32a. Limestone,. 75 mile west of Riders Mill station on the Harlem Extension Railroad about 9 miles north-northeast of Chatham
Bicia gemma
Acrotreta sagittalis taconica

No. 44a. Limestone on Valatie Kill, near the line between Nassau and Schodack townships, near the line between Troy and Kinderhook quadrangles
Acrotreta sagittalis taconica
Microdiscus connexus Walcott

No. 44b. Limestone near North Chatham
Micromitra (Iphidella) pannula
Lingulella granvillensis
Acrotreta sagittalis taconica
Hyolithellus micans
Agnostus sp.

The exact position of these localities is difficult to determine, but they seem to occur in an area of shale and quartzite closely associated with exposures of limestone, limestone conglomerate, and calcareous sandstone. The writer feels confident that these latter beds are the same as those which crop out to the south near the Hemlock School, where they are known to be of Ordovician age. It would seem, accordingly, that to the north these Deepkill beds rest adjacent to fossiliferous Lower Cambrian strata; an unconformity is implied.

Rocks in the other area contain the following faunule:

No. 29. Limestone just above the bridge at the Stockport paper mill, on Kinderhook Creek, Columbia Co., New York
Obolus prindlei
Lingulella granvillensis
Acrotreta sagittalis taconica

The assignment of an early Cambrian age to this faunule introduces difficulties of interpretation. The writer has examined the area around Stockport in detail, and these beds are almost surely the same as those that occur in a similar relationship to the Normanskill northward at Chittenden Falls and at Stuyvesant Falls, where they are generally acknowledged to be Deepkill. In view of the unusual structures observed in that vicinity it is possible

though not probable, that the beds at Stockport might differ in age from those to the north and thus be true Lower Cambrian.

Closer examination of this fossil evidence (Locality No. 29) shows that it is more compatible with a Deepkill age than it would first seem. Both *Obolus prindlei* and *Lingulella ganvillensis* belong to a small group of shells that Walcott (1912, p. 409) describes as ranging through to the Ordovician; furthermore, both species appear to be confined to eastern New York and western Vermont. The species *Acrotreta sagittalis* Walcott (1912, p. 705) also ranges into the Ordovician and occurs in "*Phyllograptus* slate" in Norway.

Here as elsewhere it is important to realize that lithologically parts of the Lower Cambrian argillite sequence so resemble the upper unit of the Deepkill that the great master of the Hudson Shale sequence, Dr. Rudolf Ruedemann, mapped important parts of the Deepkill as Lower Cambrian. Since the two sequences are unconformable and since the Lower Cambrian is exposed extensively to the north in the Troy quadrangle, it is to be expected that other Lower Cambrian localities will be discovered within the strongly folded Deepkill terrane. The fact remains that, although the "Lower Cambrian Nassau" *lithology* extends south to the New York Highlands, no Lower Cambrian fossils have been found south of the localities here discussed. On the other hand, this study and Warthin's (1949) findings in the Rhinebeck and Poughkeepsie quadrangles indicate the presence of Deepkill rocks in and south of the Kinderhook quadrangle.

On the basis of stratigraphic position, this unit is correlated with the Deepkill shale. Some outcrops of this lithology however, especially where lack of outcrop obscures the structural pattern, may be Lower Cambrian.

Normanskill terrane.—Unlike the confusing green shale terrane, the Normanskill terrane can be readily subdivided; there are three distinct members, which are believed to represent true time-stratigraphic units. This terrane with its three-fold division can be correlated on both lithologic and faunal evidence with the typical Normanskill to the north and west, as described in great detail by Ruedemann (1930, p. 96–104; 1942a, p. 88–116) and Goldring (1943, p. 99–119).

RED SHALE UNIT: This unit is generally exposed as a fissile to shaly, fine-grained shale which becomes increasingly slaty eastward. The overwhelming bulk of the unit is a distinctive dusky red, but laterally it may grade into dark gray or light green; this latter color is believed due to reduction of the ferric iron and occurs as discrete horizontal zones, along fractures, or in scattered pockets of variable size. Oil-like black films are common on the bedding planes and aid in separating this unit from stratigraphically lower red shales. Interbedded in these shales are flaggy cherts and siltstones, the undersides of some of which contain fillings of groove casts and small pits of doubtful origin (Shrock, 1948, p. 162–166, 136–145). The cherts contain a profuse radiolarian fauna, well described by Ruedemann and Wilson (1936, p. 1555–1580).

Good exposures can be studied on the hill three-quarters of a mile northwest of Ghent (C1N19E) and along the ridge two-thirds of a mile west of White Mills (C23N21E).

The red shale is complexly folded and faulted wherever exposed; its thickness, therefore, can only be estimated as about 100 feet.

This unit is well developed to the east around Chatham and vicinity but evidently thins and disappears in the western part of the quadrangle.

The red shale underlies the Normanskill black cherts along the dirt road about half a mile west of White Mills (C23N21E). Its stratigraphic position can also be determined by study of the ridge west of State Route 203 between Chatham and Valatie (C24S12E) and in the fields west of the old Rutland Railroad tracks north of Chatham (C18S6W). The synclinal interpretation of these Normanskill areas is further supported by the orientation of such fold axes as can be measured; however, in view of the limited exposure and the local variability of these plunges, this is only supporting evidence. Where one draws the base of the Normanskill is rather arbitrary in view of the underlying red shale zone in the shale and quartzite unit; in the field the writer has found it most practical to put the base of the Normanskill just above the highest occurrence of prominent interbedded 1- to 2-inch quartzites.

The only fossils known from this unit are the radiolarians and other fragmental forms listed

by Ruedemann and Wilson (1936, p. 1555–1580).

On the basis of its stratigraphic position and distinctive lithology this unit is correlated with the basal shale member of the Normanskill, as described by Ruedemann (1930, p. 98–99) from the area to the north.

MOUNT MERINO UNIT: Ruedemann (1942a, p. 89) named this unit from the prominent exposure at Mount Merino in the Catskill quadrangle to the southwest. The shale is black and fissile, and in most places the bedding planes are covered with limonitic stains. The texture is rather coarse for a shale, and the bedding-plane surfaces feel rough and gritty. The shale is naturally dull and without luster, but deformation may locally be intense enough to produce a glazed "bakelite" appearance.

The chert occurs in beds half an inch to 4 inches thick interbedded in the black shale. Thin sections show that it is a cryptocrystalline aggregate filled with microscopic quartz veins. Though more commonly black, in places it is grayish green; the surface weathers to a distinctive white or pale green. Under a hammer blow the chert breaks either with a subconchoidal surface or along incipient fractures; in the latter case the smooth surface has a peculiar vitreous luster, probably due to microscopic quartz veins along the fractures. This unit is highly resistant to erosion and forms ridges which stand in sharp contrast to the neighboring lowland underlain by shale. In some exposures thin beds of bluish-gray limestone are also interbedded with the shale.

These cherts and shales are well exposed throughout the western part of the quadrangle and may be observed on the ridge half a mile south of Chatham Center (C4S16W) or along U. S. Route 9 at Sunnyside (W27N8E).

A complete section of this unit cannot be measured in the field at any locality, but a fair estimate of its thickness may be obtained from careful mapping of outcrops, measurements of dips, and projection of beds. This technique was applied at the following localities with the indicated results:

(1) Chittenden Falls and along the road east of the creek (SW1S3E); thickness: about 200 feet
(2) Creek bed and eastward along tributary, just south of the Stockport paper mill (SW-13S3E); thickness: not more than 250 feet
(3) Synclinal remnant 1 mile east of Omi (SW-7S1W); thickness: not more than 300 feet

The best evidence of the stratigraphic position of these beds is in the bed of Kinderhook Creek at Chittenden Falls (Fig. 4). The Normanskill and Deepkill beds are folded together in a south-plunging structure, demon-

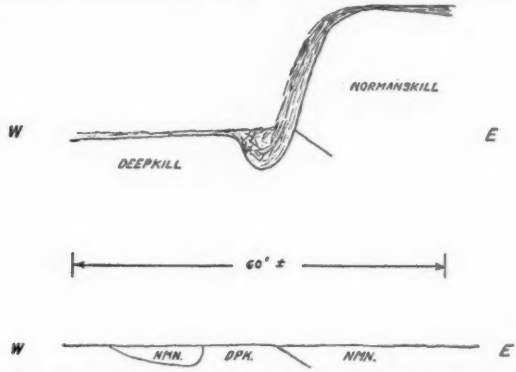

FIGURE 4.—SKETCH SHOWING STRUCTURAL RELATIONS AT CHITTENDEN FALLS

Both sections are across the bed of Kinderhook Creek; the lower section lies about 150 feet south of the upper section.

PLATE 2.—TYPICAL DEEPKILL AND SCHODACK CONGLOMERATES

FIGURE 1.—Typical Deepkill limestone conglomerate (× 1). Note sandy matrix and rounded fragments of black chert.

FIGURE 2.—Typical Schodack limestone conglomerate (× 1). Note argillaceous matrix and pitted limestone pebbles.

FIGURE 1

FIGURE 2

TYPICAL DEEPKILL AND SCHODACK CONGLOMERATES

FIGURE 1

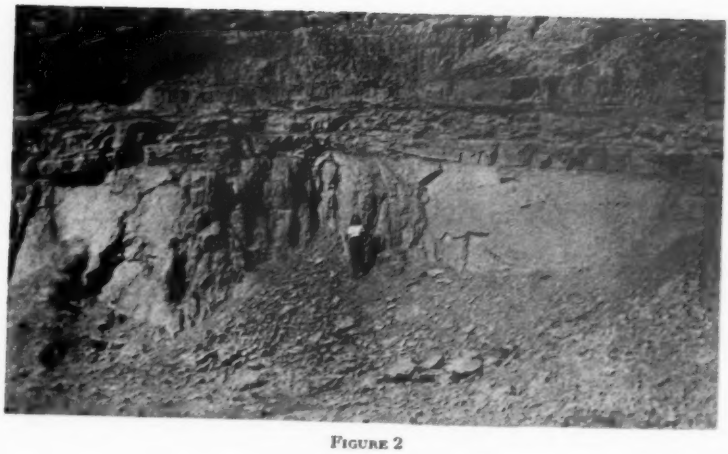

FIGURE 2

WORM TRAILS; UNCONFORMITY

strating again the synclinal nature of the Normanskill terrane. This interpretation is substantiated by the map pattern.

The fauna of the Mount Merino unit is profuse, composed mainly of graptolites, and was summarized by Ruedemann (1942a, p. 90–101).

Gurley (1896, p. 303, 304) mentions a large collection of graptolites from the cherts at Stockport. In addition, the writer has collected specimens at the localities listed below; unidentifiable fragments can be found at many other outcrops.

(1) Road cut, 1 mile northeast of Chatham Center (N7N5W)
Dicellograptus gurleyi Lapworth
D. divaricatus (Hall)?
Climacograptus sp.

(2) North bank of Kinderhook Creek, 2 miles northeast of Chatham Center (N15N6W)
Climacograptus bicornis (Hall)?
Dicellograptus sp. cf. *D. gurleyi* Lapworth
Dicranograptus nicholsoni Hopkinson?
D. cf. *D. spinifer* Lapworth
Glossograptus ciliatus Emmons?
G. cf. *G. ciliatus* v. *debilis* Ruedemann
Thamnograptus?

3) South bank of Kinderhook Creek, 1 mile southwest of Chatham Center (C10S21E)
Dicranograptus furcatus (Hall)
Glossograptus cf. *G. whitfieldi* (Hall)

(4) Just below the Stuyvesant Falls dam (W18N9E)
Diplograptus sp.
Dicellograptus sextans (Hall)

(5) Hillside, 1 mile north of Stuyvesant Falls (W27N8E)
Climacograptus bicornis (Hall)?
Dicellograptus sextans (Hall)
D. sp.
Dicranograptus furcatus (Hall)
Diplograptus calcaratus v. *incisus* Lapworth?
D. calcaratus v. *acutus* Lapworth
Nemagraptus sp.

(6) Ridge, 1 mile west of White Mills (C23N20E)
Climacograptus parvus (Hall)?
C. sp.
Dicellograptus sextans (Hall)
D. sp.
Dicranograptus cf. *D. furcatus* (Hall)
D. spinifer Lapworth?
Didymograptus?
Glossograptus ciliatus Emmons
Retiograptus geinitzianus (Hall)

(7) Road cut, ¼ mile west of White Mills (C23N23E)
Climacograptus sp.
Dicellograptus sextans (Hall)?
D. sp. cf. *D. divaricatus* (Hall)
Dicranograptus nicholsoni Hopkinson
Diplograptus sp.
Leptograptus?

(8) Boston and Albany railcut, 1 mile west of Chatham (C19N15W)
Climacograptus parvus (Hall)?
C. sp.
Corynoides curtus Lapworth
Dicellograptus sextans (Hall)
D. sp.
Didymograptus cf. *D. sagitticaulis* Gurley
Diplograptus cf. *D. calcaratus* Lapworth
D. sp.
Glossograptus ciliatus Emmons
Leptograptus cf. *L. flaccidus* (Hall)
L. sp.
Retiograptus geinitzianus (Hall)
Thamnograptus ?

(9) One mile east of Omi (SW7SOW)
Climacograptus bicornis (Hall)?
Dicellograptus sp.
Didymograptus sagitticaulis Gurley?

(10) Hillside, ¼ mile northwest of Mellenville (SW5N5W)
Climacograptus parvus (Hall)
C. bicornis (Hall)
Dicellograptus sextans (Hall)
D. sp.
Dicranograptus furcatus (Hall)
Didymograptus sagitticaulis Gurley?
Diplograptus calcaratus Lapworth?
Thamnograptus?

(11) Three miles northeast of Brick Tavern, just south of state highway 66 (SW27S6W)
Climacograptus sp.
Dicellograptus sextans (Hall)
D. sp.
Dicranograptus cf. *D. ramosus* (Hall)
Didymograptus?
Diplograptus sp.
Leptograptus flaccidus (Hall)?
Retiograptus geinitzianus (Hall)
Thamnograptus?

(12) Ridge, ¼ mile east of Stottville (SW27N11W)
Climacograptus parvus (Hall)
C. bicornis (Hall)?
Dicellograptus sextans (Hall)?
Dicranograptus furcatus (Hall)
D. cf. *D. ramosus* (Hall)
Diplograptus sp.
Nemagraptus sp.

(13) Hillside, 2 miles north of Mellenville (SW17N5W)
Climacograptus bicornis (Hall)
C. sp.
Dicellograptus sextans (Hall)
D. sp.
Dicranograptus? cf. *D. spinifer* Lapworth
D. nicholsoni Hopkinson?
Glossograptus ciliatus Emmons

On the basis of similarity of fauna, lithology, and stratigraphic position this unit in the Kinderhook quadrangle is properly correlated with the Mount Merino chert and shale in the adjacent quadrangles to the west.

AUSTIN GLEN UNIT: Also named by Ruedemann (1942a, p. 89) from its type locality in the Catskill quadrangle, this unit crops out in the Kinderhook quadrangle as resistant ledges of massive graywacke with interbedded shale.

PLATE 3.—WORM TRAILS; UNCONFORMITY

FIGURE 1.—Plaster cast of problematic impression, possibly worm trails, Stuyvesant Falls.

FIGURE 2.—Silurian-Devonian limestones unconformably on folded Deepkill (?) beds at Mount Ida.

Most of these shales are fine-grained, black, and fissile, but occasional outcrops are transitional from shale to graywacke in both texture and color. Most of the graywacke beds are massive, and individual beds are up to 20 feet thick. In hand specimen it is gray to dark-yellowish-brown, medium-grained rock that weathers a dirty gray. Poorly developed ripple marks occur in places; the undersurface of some beds reveals flow casts about 1 inch in width (Shrock, 1948, p. 156–161). Neither graded bedding nor cross-bedding is apparent. At one locality the graywacke is interbedded with the underlying chert at the contact.

In addition there are also beds of dusky blue, very fine-grained limestone up to 6 inches thick. They are best developed in the western outcrops and can be seen in the vicinity of Stockport.

In thin section the graywacke is poorly sorted and lacks even a suggestion of bedding; most of the fragments are subangular, and many show strain shadows. Quartz and the argillaceous matrix are the most important constituents and together constitute about two-thirds of the rock. The remaining third includes fragments of chert, schist, and siltstone, plagioclase, iron oxide, and calcite, in order of descending importance.

Graywacke is well exposed along the east side of Kinderhook Creek between Stockport and Chittenden Falls (SW6S4E) or along State Route 66 north of Chatham (C30N10W).

As the Austin Glen is not in contact with younger beds and a continuous section is nowhere exposed within the quadrangle, the preserved thickness must be estimated. About 2 miles northwest of Chatham (C24S15W) scattered outcrops in a field extend about 1000 feet across the strike. As the dip remains at 45°–50° E. across the traverse, the beds probably have not been repeated by folding. If this represents an undisturbed section, then the unit here is about 700 feet thick. Similar measurements and assumptions in the bed of Kinderhook Creek just south of Stockport show an apparent thickness of at least 600 feet.

This unit occurs in the center of synclinal remnants, and, except where the structure is complicated by faulting, it lies adjacent to the Mount Merino unit.

Several problematic outcrops occur northwest of Mellenville (SW5N17W) (SW11N10W). At these localities the graywacke is poorly exposed, mainly as ridges in the road bed, and its relation to the other stratigraphic units is not clear; glacial cover is thick, and other units do not crop out near by. On the map the writer has interpreted these isolated outcrops as synclinal remnants of indigenous strata and has surrounded them with a hypothetical belt of Mount Merino beds, consistent with the pattern so conspicuous elsewhere. That these rocks belong to the Austin Glen is verified by study of hand specimens and thin sections, but very possibly they are glacial in origin.

That the Austin Glen overlies the Mount Merino is best shown by the map pattern and, in the field, near the Stony Kill and the tracks of the Boston and Albany Railroad 1½ miles north of White Mills (C20S14W).

This unit has yielded fossils elsewhere, principally graptolites and eurypterids, but none were found in this quadrangle.

Since the lithologies and stratigraphic positions are identical, there can be little doubt of the correlation of this unit with the Austin Glen member to the west.

Black shale.—A small outcrop occurs 150 feet north of Pitt Hall, a summer camp near Old Chatham, on the west slope of a low ridge (NW10N4E). The black shale is exposed in a thicket and is isolated from the other bedrock by the soil and glacial cover. It is a brittle, heavy, phyllitic rock, and what is interpreted as cleavage strikes N. 30°W. and dips 50°E. On the crest of the ridge 200 feet to the north olive argillites strike N. 10°E. and dip about 25°E. Just west of this ridge is a discontinuous belt of calcareous sandstone.

Attempts to correlate this shale suggest several alternatives. The presence in the vicinity of olive argillite and calcareous sandstone suggests that this black shale may represent the thin black chert and shale unit sometimes found with these lithologies. It is possible, though less likely, that the black shale is the higher interbedded shale and limestone unit, locally developed here by some quirk of deformation. A third alternative is to correlate this black shale with the phyllitic black slate in the eastern sequence. The same contrast in the strike of the cleavage is observed on a large scale where the Trentonian black slate lies on

the Lower Cambrian slate east of the Chatham thrust.

Mount Ida.—Mount Ida is an erosional remnant of Upper Silurian and Lower Devonian limestone, about a quarter of a mile square, near the southwest corner of the quadrangle (SW8N10E); it marks the only occurrence of these rocks in the Kinderhook quadrangle. Though smaller, this hill is comparable in its structural relations and stratigraphy to the classic outlier at Becraft Mountain, a few miles to the southwest in the Catskill quadrangle.

The strata in and underlying Mount Ida can be observed best in the quarry of the Catskill Mountain Stone Company, entered from State Route 66. The uppermost unit along the east rim of the quarry is 10 feet of coarsely crystalline, light-gray limestone which weathers to a rough, light-brown surface. Fossils are abundant, and a large collection of crinoids, brachiopods, and corals is easily obtained. The writer has not studied this fauna in detail; Dr. Goldring identified the collection as typical of the Lower Devonian Coeymans limestone. For a complete description of this fauna the reader is referred to the excellent discussion by Goldring (1943, p. 151–158).

Below this coarse limestone unit is 80 feet of rather uniform fine-grained grayish-black limestone; the rock weathers to a smooth light-gray surface that brings the few fossils present into relief. The limestone contains many veins of white calcite, especially along the bedding planes. It is a very tough rock and breaks only with a hard blow of the hammer. On the basis of its physical characteristics and conformable position below the upper Coeymans limestone this unit is correlated with the lower part of the Coeymans and the Upper Silurian Manlius limestone. The total thickness of the Manlius and Coeymans exposed here is comparable to the 100 feet present at Becraft Mountain.

The limestone strata are warped into gentle flexures whose axes trend about N. 15°E. Much of the white calcite is striated, apparently by bedding-plane slippage; these striae all trend near N. 65°W., parallel to the differential movement in the direction of dip. These Upper Silurian and Lower Devonian limestones overlie with angular unconformity (Pl. 3, fig. 2) a folded and beveled argillite sequence of probable Deepkill, though possible early Cambrian age.

Sequence East of the Chatham Thrust

General description.—The most striking contrast of this sequence with respect to the western sequence is the uniformly higher metamorphic grade of the rocks. Like the beds of the western sequence most of these rocks were originally argillites, but metamorphism here has proceeded almost universally to the slate level, and some of the strata have been altered to phyllites. This higher metamorphic grade is reflected in the topography, which changes sharply from the western lowland into the eastern rolling upland along the Chatham thrust. Deformation has, in general, been more severe than to the west; even the massive quartzites have been locally bent into sharp folds. Fossils are present in some of the limestones in the sequence, but most of the rocks are essentially unfossiliferous slate (Fig. 5).

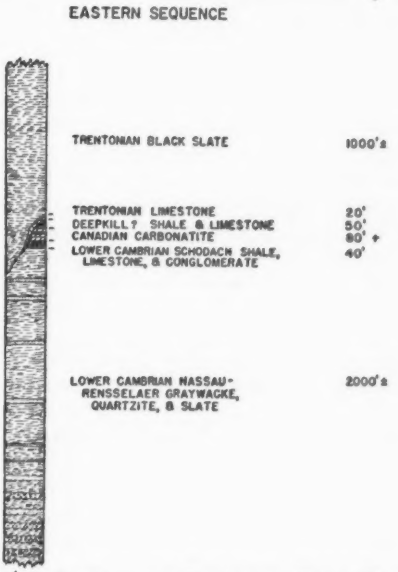

FIGURE 5.—COLUMNAR SECTION OF ROCKS EAST OF THE CHATHAM THRUST

Green slate terrane.—This terrane is similar to the green shale of the western sequence in that most of the outcrops are an altered, grayish-green shale; but unlike the sequence to the west, this terrane contains no key beds which

are traceable over considerable distances. A number of distinctive lithologies can be recognized, but these beds cannot be traced far along the strike. This is due in part to the greater deformation and poor exposure, but it probably also reflects an originally small areal extent of the marker horizons. Accordingly, the structure in this sequence is far less clear than to the west, and the dating of the units is correspondingly less secure.

GREEN SLATE: Grayish-green slates, generally phyllitic, are by far the most common rocks; from their outcrop pattern and association with all the other rock types they may be considered as a thick series equal stratigraphically to the whole of the green-slate terrane—*i.e.*, the "groundmass" through which the other units are scattered. In this terrane one can only determine the sequence of these distinctive lithologies within the green slate and estimate the thickness of the entire series.

Bedding in this slate can rarely be traced because of the strong development of cleavage. A few outcrops, however, contain siltstones interbedded in the slate and permit determination of the structure; such localities are rare but without exception reveal the intense folding that would be expected from the well-developed cleavage.

While these slates are most commonly grayish green, prominent zones of purple, red, and rarely dark gray are known. The bright-red slates are usually in close association with a zone or zones of interbedded slates and thin siltstones. The purple shales and slates are exclusively interbedded in thick-bedded graywackes and quartzites.

Good outcrops of this slate unit can be studied in the road cuts east of Philmont (S2N14E) or in the fields west of Sutherland Pond (E10S5W).

There is no way of accurately determining the thickness of this slate series. From its areal distribution its thickness is estimated at about 2000 feet.

The evidence of the stratigraphic position of this green-slate terrane is essentially paleontologic. The writer knows of no locality in this quadrangle where the structural relations of the green-slate terrane and black-slate terrane can be definitely established; wherever the two occur close together, the bedding has been completely obscured by the cleavage. The green-slate terrane is considered much older than the black-slate terrane and is dated as Lower Cambrian or older by the presence of a Lower Cambrian fauna high in the sequence. Some of this sequence of slates may be younger than Lower Cambrian though no undoubted fossils have been found to support this view.

The green slate east of the Chatham thrust is assigned chiefly to the Lower Cambrian on the basis of the following:

(1) The major thrust fault, the Chatham thrust, which separates the western area of green argillite from the eastern, is clearly exposed at several localities which are described in the section on Large-Scale Structural Features. Since Lower Cambrian rocks lie beneath the dominant Deepkill shales west of the Chatham thrust, they may be expected to lie exposed east of the thrust.

(2) The map shows that outcrop bands of the Ordovician calcareous sandstone-limestone conglomerate unit and the interbedded shale and limestone unit which crisscross the region west of the thrust are absent east of it.

(3) The massive layers of graywacke and quartzite, widespread east of the thrust and clearly related to the Rensselaer graywackes, are unknown to the west.

(4) An Early Cambrian fauna abounds in the limestone and limestone conglomerate which form a syncline high on Ashley Hill, representing apparently a zone high in the stratigraphic sequence.

RENSSELAER GRAYWACKE AND QUARTZITES: The Rensselaer graywacke, first designated as grit, was described in detail by Dale (1893) and more recently by Balk (1953). As originally used, the term applies to a rather thick series of graywackes and conglomerates with interbedded purple and green shale. However, for reasons to be discussed, the writer felt it advisable to include a series of massive green quartzites with the discussion of the Rensselaer graywacke.

Typically the graywacke is a medium- to coarse-grained, locally conglomeratic, massive dusky-green rock. Interbedded in this series of graywackes are slates, in most places purple or green but locally black. This sequence is very resistant to weathering, and where well developed, as in the Troy quadrangle to the north, it forms a conspicuous upland. These

beds—like most of those in the eastern sequence—are full of white quartz veins; they may also contain feldspar. Balk (1953, p. 824–827, Pl. IV) has discussed the conglomeratic phases of this unit; where observed in the quadrangle the pebbles are mainly white quartz, and the matrix is a deformed quartz-chlorite phyllite, almost schistose in places. The largest fragment noted was a block of altered granular green quartzite 15 by 6 by 4 inches.

Thin-section study reveals a poorly sorted rock in which some of the grains are subrounded. Its composition is roughly 50 per cent quartz, 25 per cent chlorite, 15 per cent plagioclase and microcline, the remainder iron oxide, zircon, tourmaline, and sphene.

The massive quartzite beds, where typically developed, are generally a moderate green; the few exceptions are a very dusky red. Thicknesses of 3–30 feet have been observed, and 20-foot beds are the most common; these resistant masses may rise from the slate as sharp ridges (but some of the ridges are slate). The quartzite is rather fine-grained, in contrast to the graywacke, and the broken surface has a vitreous luster. Like the graywackes these beds usually yield to deformation in broad, gentle folds, but locally they may be sharply folded; the strong cleavage in the slate may continue in the quartzite as a poorly developed fracture cleavage. Pyrite is disseminated through some hand specimens; pockets of brown manganese and iron oxides are common. These massive quartzites are generally associated with sequences of thin interbedded siltstones and shales which closely resemble the upper unit of the green shale terrane in the western sequence. Green slates are the usual variety found with both the massive quartzites and the thinner siltstones, but zones of bright-red slate are widespread. This red slate is very similar to the basal red Normanskill shale but lacks its characteristic black stains.

Microscopic study shows that the quartzite is much finer-grained than the graywacke; most of the quartz grains are subrounded and show strain and recrystallization along their boundaries. The average composition of the quartzite is approximately 90 per cent quartz, 5 per cent chlorite, 2 per cent iron oxide, and 2 per cent plagioclase, with traces of zircon, tourmaline, sphene, and apatite. Thus the same mineral suite is present in both the graywacke and the quartzite, but the proportions differ.

While these end members are easily distinguished, many rocks of this general character occur which seem to represent transitional types in color, texture, and composition. Detailed study confirms the impossibility of separating the quartzites and the graywackes as distinct units. A finely conglomeratic lithology present at most sizable graywacke exposures can be observed in the same outcrop with typical quartzites at Old Chatham (NE16N11E), Red Rock (E16N5W), and 1 mile north-northeast of Old Chatham in the creek bed (NE25N16E). The writer has attempted to map (Pl. 1) the approximate borders of what is generally implied by the name "Rensselaer graywacke," but its vertical gradation into quartzite makes the position of such a boundary rather arbitrary. Balk (1953, p. 831–832) experienced similar difficulties in the Red Rock-Spencertown area.

The best outcrops of these lithologies in the Kinderhook quadrangle are found in the hills east of Spencertown and along the road to Red Rock (Pl. 1).

The total thickness of this graywacke-quartzite unit as exposed in the Kinderhook quadrangle is estimated at 1500 feet.

The typical graywackes are developed only at three places in the quadrangle—in the town of Austerlitz and near the villages of Old Chatham and Brainard. The quartzites have a much wider distribution and seem to be scattered throughout the green-slate terrane.

The relationship of the graywacke to the other units of this sequence is not easily determined. The outcrop area in Austerlitz was first studied by Ruedemann (1930, p. 123–130); he correlated the graywacke with the Devonian strata across the Hudson River in the Catskill Mountains and considered the Austerlitz area an erosional remnant resting unconformably upon older units. Balk (1953, Pl. 1, sections 31–33) considered the same graywacke area a part of the surrounding slate sequence and interpreted the structure as synclinal. The present writer has studied the Austerlitz area in detail and feels the lack of critical exposures and the conflicting structural evidence do not permit

choosing between an anticlinal or synclinal interpretation in this area.

In the Old Chatham area poor exposures again preclude any confident statement on the structural relations.

It is only at the third outcrop area near Brainard that these relations may be hopefully studied. At the old East Nassau quarry, just within the Troy quadrangle, the graywacke is unusually well exposed in a cliff face. Balk (1953, p. 830, Pl. 1, section 29) studied this area carefully and concluded that the graywacke here is anticlinal; Bucher and the writer also investigated the quarry area and reached the same conclusion.

As the graywacke is interbedded in the green-slate terrane and is present only in isolated outcrop areas, the writer questions whether the graywacke could be anticlinal in one place and synclinal in another. Therefore, on the basis of the area where the relations can be best observed, all three graywacke areas are interpreted as anticlinal, and the graywacke is placed below the quartzite and at the base of the green-slate terrane.

The only fossils reported from the Rensselaer graywacke were found at Old Chatham and Brainard and described as *Oldhamia* cf. *O. occidens* by Vaughan and Wilson (1934). On this basis the Rensselaer was assigned an Early Cambrian age. Ruedemann (1942b, p. 5–17) discounted these specimens as pressure effects in shale and believed the true *Oldhamia* represented a worm's feeding trail.

Because of their similar lithologies and lateral continuity, the graywackes and the overlying quartzites are correlated with the Rensselaer graywacke and the "Nassau beds," respectively, as described in the adjacent Troy quadrangle (Ruedemann, 1930, p. 83–84, 123–130).

SCHODACK SHALE AND LIMESTONE: A remarkable rock sequence crops out on the west ridge of Ashley Hill (NE12S18E). It begins with a dark-gray quartzite and is succeeded, by a sequence of limestone, shale, and limestone conglomerate which is not known elsewhere in the quadrangle. The basal part of this unit is dark-gray, tough, medium-grained quartzite that weathers to a light-gray granular surface. It is composed of about 95 per cent quartz with only traces of iron oxide, siltstone fragments, plagioclase, tourmaline, and zircon. The quartz grains are all at least subrounded, and most of them show marked strain shadows. In places the rock is slightly calcareous and reacts with dilute hydrochloric acid.

The quartzite is overlain by about 10 feet of gray shale, shaly limestone, and one bed of crystalline limestone. The latter limestone is a medium-grained rock containing a few rounded quartz grains and abundant trilobite fragments. A fresh surface is medium gray but weathers light gray and rough.

These beds are followed by a layer of limestone conglomerate at least 15 feet thick. The matrix is somewhat sandy, but predominantly argillaceous. The pebbles are mainly of two types: a foreign fine-grained bluish-gray limestone and the underlying crystalline limestone. This conglomerate bears a superficial similarity to the limestone conglomerate in the western sequence but differs in the absence of orange limonitic flakes and black chert fragments and in having an argillaceous matrix and distinctive pitted pebbles (Pl. 2, Fig. 2).

Dale (1904, p. 22–24) described the Ashley Hill locality in detail and concluded that the structure was synclinal. The writer found Dale's outcrops without difficulty and in general agrees with his structural interpretation. The conglomerate, therefore, is believed to be the youngest unit present on Ashley Hill.

Dale (1893, p. 314) cites the occurrence of *Olenellus* and *Hyolithellus micans* in the pebbles of the conglomerate. Faunas from pebbles, of course, give only a maximum age, but comparison of samples of the trilobite limestone from Ashley Hill with samples (in the New York State Museum) from Troy and Schodack Landing leaves no doubt of the identity of these three limestones. Large Lower Cambrian faunas have been obtained from these limestones at Troy (Ruedemann, 1930, p. 80–81) and Schodack Landing (Goldring, 1943, p. 83). Dr. Christina L. Balk (letter to Professor W. H. Bucher) has found *Elliptocephala asaphoides*, *Hyolithellus micans*, *Lingulella* cf. *granvillensis*, *Botsfordia caelata*, *Helcionella rugosa*, *Calodiscus lobatus*, *Fordilla troyensis*, and *Hyolithes* sp. at the Ashley Hill locality. The writer identified *Botsfordia caelata* from a crystalline limestone pebble in the Ashley Hill conglomerate.

On the basis of this lithologic, stratigraphic

and fossil evidence the conglomerate and the underlying limestone and shale are correlated with the Schodack shale and limestone. The underlying gray quartzite is probably equivalent to the Diamond Rock quartzite (Ruedemann 1930, p. 82–83).

INTERBEDDED SHALE AND LIMESTONE: About 1 mile south of the conglomerate ledge on Ashley Hill interbedded limestones and shales are exposed on a hilltop (NE20S18E). These beds appear identical to the Deepkill shale and limestone unit in the western sequence, and on the hillside are several interbeds of limestone conglomerate 8–20 inches thick, one of which contains fragments of black chert.

The correlation of these beds is uncertain. Their appearance and the presence of chert fragments suggest a Deepkill age. Yet Dale (1904, p. 24) in discussing this outcrop considered it definitely related to the Lower Cambrian beds on Ashley Hill, which lie in the direction of strike. Furthermore, Walcott found *Microdiscus connexus* and *Linnarsonia sagittalis* var. *taconica* in these limestones and assigned them to the Lower Cambrian (Dale, 1893, p. 314). The stratigraphic position of these beds must therefore remain an open question.

Ordovician carbonate rocks.—This terrane is represented only in a belt of scattered outcrops along the trace of the Chatham thrust. The preservation of these beds along this line is believed to be due to their emplacement as slivers or blocks "dragged down" along a thrust fault; they were separated from one another by erosion, either before or after the tectonic movement. The structure is believed comparable to the relations at Bald Mountain, Washington County, New York, as described by Cushing and Ruedemann (1914, p. 75–80).

The individual outcrops, from south to north are:

(1) Two low hills 1 mile north of Philmont (S13N15E). Apparently first described by Bishop (1890), these beds can be studied best in the abandoned quarry on the southeast slope of the ridge. Most of the beds are a dusky-blue, massive limestone that weathers light gray; interbedded with it are a few beds of fractured, medium-gray dolomite which weather light brown. Some of the limestone is very sandy, and weathering produces a peculiar "wavy" effect. The beds are about 50 feet thick and strike N. 45°E.; on the southeast they dip 75°E., on the northwest 65°E. The hills are surrounded by lowlands, and the nearest bedrock is a rail cut in green slate ¼ mile away. Consequently, the relations between limestone and slate are unknown at this locality.

Bishop (1890) reported "Trenton" fossils from this locality and listed *Chaetetes compacta* Billings, *Monticulopora lycoperdon* Say, *Orthis testudinaria?* Dal, *Murchisonia gracilis*, and *Orthoceras* sp. However, Marshall Kay found *Lecanospira* sp., and the writer found *Maclurites?* and *Eremoceras?* in these limestones.

(2) Two small knolls beside the old Rutland Railroad track, 1½ miles north of Chatham (C23S6W), also apparently first described by Bishop (1886). These outcrops are lithologically like those at the last locality. The writer found no fossils though Bishop lists *Leptaena sericea*, *Strophomena alternata*, *Murchisonia gracilis?*, *Maclurea?*, *Orthoceras?*, *Prilodycta* n. sp. from these outcrops and one "a mile to the north", which the writer was unable to locate. This locality is of considerable interest in that it shows the presence of a thrust. The limestone beds strike about N. 20°E. and dip 50°E. Immediately beneath the limestone at the thrust contact is a thick zone of crushed Normanskill shale; 100 feet west of the thrust the Normanskill shale strikes due north and is intensely folded.

(3) Isolated ledge in valley of small stream, ¼ mile south of dirt road (E10S1E). Beds of the same dusky-blue limestone strike N. 40°E., dip about 60°E.

(4) Yard of the Rock City schoolhouse (E9S3E). The interbedded dolomite and limestone sequence is as well developed here as at the first locality; the beds at the two outcrops appear to be identical. The dolomite has been fractured and filled with calcite veins, but the limestone has yielded to deformative stresses by flowage. Bedding strikes N. 60°E., dips 75°E. The only fossils known are a few brachiopod fragments found by Professor Marshall Kay.

(5) Hill, ¼ mile northeast of Rock City schoolhouse (E7S5E). The following section (descending) can be pieced together from exposures on the east side of the hill:

Feet	
	Glacial cover
15	massive, fractured medium-gray dolomite with nodules of black chert

4 massive, fine-grained, medium-gray limestone
16 massive, granular, medium-gray dolomite
6 soil and talus cover
12 massive, fractured, medium-gray dolomite
5 soil cover
5 massive, siliceous, light-gray dolomite
2 very light-gray, fine-grained, cross-bedded quartzite
4 massive, light-gray dolomite
1 light-gray dolomite that weathers to a laminated surface
9 massive, light-gray dolomite
30 soil and talus cover
dark-gray-green and red fissile shale, vertical cleavage (?) strikes N. 30°E.

The cross-bedding shows that the sequence is right-side up. The carbonate rocks strike N. 30°E., dip 20°W. on the east side of the hill.

On the west side of this hill the contact of the carbonate rocks with the underlying grayish-green shale is exposed. The situation is comparable to that at the second locality. The underlying shales are pulverized below the contact, but just to the west they strike due north and dip steeply to the east. The overlying limestones, however, are thrown into a series of overturned folds; these beds strike N. 45°E. and dip 40°–65°E.

It appears then that the carbonate rock sequence is essentially synclinal at this locality; along its western margin it is in definite thrust contact with the underlying shales. No fossils were found at this outcrop.

(6) End of ridge, overlooking Old Chatham (NE13N11E). The same interbedded dolomite and limestone beds occur here on the extreme north end of the ridge, where they form a steep west-facing cliff. These strata crop out over a rather small area, are surrounded by drift and soil cover, and could not be traced even short distances. The beds strike N. 20°E., dip 45°E. A quarter of a mile north of the end of the ridge the deep ravine of a west-flowing stream shows continuous exposure of bedrock. The carbonate rocks atop the ridge can be traced down the north end of the ridge to within a few hundred feet of the ravine, but do not occur in the ravine where they should appear by projection. It is inferred that the outcrop atop the ridge is synclinal.

In summary, this terrane is composed of a belt of six outcrops of interbedded limestone and dolomite. The greatest thickness observed is about 80 feet, but the total thickness is undoubtedly greater. The fossils collected during the present study indicate a middle Canadian age.[1] The structural relations render it improbable, if not impossible, that these outcrops are anticlinal and represent an underlying carbonate sequence protruding through an overlying shale sequence. The evidence is strong, though not compelling, that the carbonate sequence rests upon the Lower Cambrian shale.

The relationship of these Canadian strata to similar beds near by should be noted. To the south the Rochdale limestone also contains *Lecanospira*; it is lithologically similar to the limestone at locality No. 1, and the two units are doubtlessly correlative. The *Lecanospira* horizon is apparently present near the top of Weaver's (1953, Ph.D. thesis, Univ. of London) "undifferentiated Cambro-Ordovician" carbonate sequence.

Weaver does not discuss the strata underlying his Upper Cambrian-Canadian carbonate sequence in the eastern part of the Copake quadrangle; he interprets the green slates to the west as facies of the carbonate rocks. The present writer considers it more probable that these slates are principally Lower Cambrian. If this interpretation proves correct, then the carbonate rocks seem to rest upon Lower Cambrian slate here as in the central part of the Kinderhook quadrangle. In the eastern Copake quadrangle, the *Lecanospira* zone is separated from the Lower Cambrian slate by several hundred feet of Upper Cambrian and Canadian carbonate rock. In the Kinderhook quadrangle, however, about 8 miles west from the strike of the Copake carbonate rocks, it lies directly on it. This suggests a westward transgression of the Late Cambrian-Canadian seas upon an axis of Lower Cambrian slates.

Black-slate terrane.—The prominent unit in this terrane is a heavy, fine-grained black slate, in most places metamorphosed to a shiny phyllitic appearance. The cleavage planes are sharply defined and closely spaced, and striae are visible in some exposures. Bedding is

[1] If further study confirms the identification of the fossils reported by Bishop, Trentonian rocks are present as well.

obscured by this cleavage, and even along the rarely exposed contacts structural relations are obscure. Small pyrite crystals have been observed, and white quartz veins are common. Good exposures of this slate are found along the roads leading south from either Old Chatham (NE10N16E) or New Concord (E29S16W).

In the extreme southeast corner of the quadrangle two outcrops of limestone seem to be associated with this black slate (SE11N2W) (SE7N5W). This limestone is probably not more than 20 feet thick, but a good cleavage is developed, and the bedding is not distinct. The rock is dark gray and very fine-grained; it weathers light gray. No fossils were found in these two outcrops, but this limestone is interpreted as the basal limestone unit of the black slate—as developed to the south in the Copake quadrangle (Weaver, 1953, Ph.D. thesis, Univ. of London).

The thickness of this black slate is estimated as on the order of a thousand feet, based on the relative size of its outcrop areas.

The contacts of this unit (Pl. 1) with adjacent units do not have the shape typical of a contact between conformable beds in a folded area. (*Cf.* the contacts west of the Chatham thrust.) So irregular a contact suggests a possible unconformity between the younger black slate and the older green slates and quartzites, but in the field poor exposures and prominent cleavage mask this unconformity.

This black slate probably is Trentonian and lies unconformably on the Lower Cambrian green slate, because

(1) It is lithologically identical to the black slate of an area of similar shape and extent that lies in line with the southward projection of its axis in the Copake quadrangle (Weaver, 1953, Ph.D. thesis, Univ. of London).

(2) Reconnaissance studies in the Pittsfield quadrangle show that this black slate can be traced into what is called "Walloomsac slate" to the northeast (Prindle and Knopf, 1932, p. 269, 274–275).

(3) The writer has found no fossils in this black slate. In the corresponding black slate of the Copake quadrangle fossils are so scarce that it seemed at first to be unfossiliferous. After much search, Weaver found Trentonian fossils in the western area at one locality, after having located several fossil localities near the base of the slate in the eastern belt.

The apparent absence of graptolites from this black slate makes it improbable that it is Normanskill, which immediately to the west abounds in graptolite remains. The absence of chert beds and limestones and its great thickness make correlation with the black shale of the Deepkill improbable. It might, however, be a facies in the Lower Cambrian, but it would be a facies not yet recognized in this region.

The writer adopts the simplest hypothesis as the most probable on the basis of available evidence and dates the black slate as Trentonian.

Correlations

The preceding section has treated the stratigraphic succession on the two sides of the Chatham thrust and correlated the various units with formations in neighboring quadrangles. It is imperative now to establish the relationship in time of the units in the eastern and western sequences of the Kinderhook quadrangle. It is also desirable to examine certain discrepancies that exist between the geologic map of this quadrangle and those of adjacent areas.

The eastern sequence of the Kinderhook quadrangle consists of Trentonian slates and Canadian carbonate rocks resting unconformably upon a Lower Cambrian slate and quartzite sequence. The western sequence is interpreted as a conformable succession of Deepkill and Normanskill beds and possibly some older rocks at the base.

The correlation of the Deepkill of the western sequence and the Canadian carbonate rocks along the Chatham thrust and southeast in the Copake quadrangle requires clarification. Stratigraphers in the Hudson Valley tend to think of the Deepkill and Canadian as more or less synchronous units, apparently basing this belief on Ruedemann's paper on Beekmantown graptolites (1902). More recent work has strongly suggested that the Deepkill is younger than generally assumed; it is probably largely Chazyan but begins in the upper Canadian. If this correlation is accepted for the moment without the evidence, then the Deepkill is

younger than the Canadian carbonate rocks of the eastern sequence, and there is no problem in their juxtaposition, simply because the two units are not time equivalent.

In that case the Deepkill shale must originally have lain in normal succession on top of some middle Canadian limestone member over large areas. While this succession is merely suggested as a possible interpretation of a few localities in the Kinderhook quadrangle, it is probably well preserved in the quadrangles to the south. In the Rhinebeck quadrangle, which adjoins the Copake quadrangle on the southwest, Warthin has found Deepkill graptolites at a point half a mile east of the top of the "Wappinger limestone" in a shale belt that adjoins and parallels the long, narrow limestone belt. (Unpublished progress report on the Rhinebeck quadrangle, on file in the New York State Museum in Albany). His studies will shed much-needed light on these relations which are made so difficult by the deceptive similarity between some Lower Cambrian and Deepkill lithologies as well as between Normanskill and younger Trentonian black shales.

The other problem that must be faced is that of the time relations of the Trentonian black slate and the Normanskill formation of the western sequence. Some workers have suggested that these two units are facies of the same formation and therefore of the same age. However, available fossil evidence is definitely against such an interpretation. Weaver (1953, Ph.D. thesis, Univ. of London, p. 94) states that the fossils of the black slate seem to relate it to the Snake Hill formation, which is Middle Trentonian and younger (Kay, 1937, p. 272, 273). Cooper and Cooper (1946) have established the age of the true Normanskill fauna as essentially Bolarian and possibly early Trentonian.

In addition, the Trentonian black slate rests with unconformity on beds of Early Cambrian age in this quadrangle; farther south it rests on a variety of stratigraphic units. This indicates folding and considerable erosion before the deposition of the Trentonian black shale. In contrast, the Normanskill is underlain by a thick conformable sequence that shows no sign of such events prior to the deposition of any part of the Normanskill.

The writer's geologic map (Pl. 1) conflicts somewhat with maps of adjacent quadrangles. Along the southern border there is general agreement with Weaver's (1953, Ph.D. thesis, Univ. of London) findings in the Copake quadrangle. However, Weaver interprets the southward continuation of the green-slate terrane as Upper Cambrian, on the basis of the similarity of the quartzites to quartzite zones in his eastern Upper Cambrian carbonate rocks. The writer prefers to consider these beds Lower Cambrian on the basis of the massive green-quartzite exposures that extend in a chain along this belt of slate from the southern part of the Copake quadrangle to the northern edge of the Kinderhook quadrangle. The relations at Ashley Hill show conclusively that the quartzites in that vicinity are Lower Cambrian or older. Hand specimens of the green quartzites from the two quadrangles are indistinguishable. This of course does not preclude the possibility that some of the green slates may be younger, but the writer feels that most of the green-slate terrane is best considered Lower Cambrian.

The Cherry Hill locality in the Catskill quadrangle has already been discussed. The discovery of Deepkill graptolites in beds mapped as Lower Cambrian by Ruedemann suggests that much of the unfossiliferous "Lower Cambrian" in that quadrangle and elsewhere may be much younger.

Formation boundaries along the western margin of the map coincide approximately with those mapped by Goldring (1943, Map 1) in the Coxsackie quadrangle, but certain adjustments are necessary. On the basis of reconnaissance mapping Goldring (1943, p. 292, 295) interpreted the belt of Normanskill exposed between Stuyvesant Falls and Stottville as a fenster of the underlying beds showing through what she considered to be overthrust "Nassau" and "Schodack" beds. The present study, however, shows that large parts of these "Lower Cambrian" beds are of Deepkill age. While complications due to thrusting are present along the Normanskill belt, the writer believes that a synclinal interpretation of the belt better fits the field relations.

Ruedemann (1930) mapped a wide belt of Lower Cambrian reaching almost across the south boundary of the Troy quadrangle. The writer, however, is convinced that here as well

much, though not all, of this belt is of Deepkill age. North of North Chatham in the Kinderhook quadrangle (N5S15E) are a number of outcrops of interbedded shale and limestone, calcareous sandstone, and limestone conglomerate. These beds strike across the quadrangle boundary into beds mapped as Schodack. Yet comparison of these exposures with the beds at Ashley Hill of acknowledged Early Cambrian age, and with the Deepkill lithologies near the Hemlock School reveals only a general similarity to the former, but a striking likeness to the latter.

Dale (1904) mapped both fossil localities and prominent lithologies in this belt of rocks in the Troy quadrangle and northward. The association of some of the limestone conglomerates with near-by Deepkill fossil localities is unmistakable. Comparison of this pattern in the Kinderhook quadrangle suggests that in both places the Deepkill wraps conformably around synclinal remnants of Normanskill.

One reason for including many of these beds in the Lower Cambrian has been the presence of *Oldhamia occidens* at several localities near the village of Nassau. Sollas (1887), who originally described *Oldhamia*, interpreted it as a structure ("*Ausweichungsclivage*") and not as an organic impression at all; since that time others have expressed similar views. Vaughan and Wilson (1934) describe *Oldhamia* cf. *occidens* from the Rensselaer graywacke and assigned the formation an Early Cambrian age. Later Ruedemann (1942b), believing the Rensselaer graywacke to be Devonian, discounted these specimens as pressure effects. Yet in another article (1942c, p. 19–20) in the same bulletin, he described an *Oldhamia* from the Ordovician of Gaspe. In view of the haggling over just what *Oldhamia* represents, and over what is and what is not a true *Oldhamia*, it can hardly be considered a Lower Cambrian index fossil.

More promising, but still subject to doubt, are the inarticulate brachiopods as indicators of a Cambrian age of the beds in question. All the genera cited are long ranging, and identification of species in the fragmental material most commonly found in these beds is difficult.

Professor W. Charles Bell has studied these inarticulate brachiopods in recent years and writes (1941, p. 195–196):

> "The taxonomic importance of internal characters among brachiopods has been emphasized greatly by the comparatively recent studies of Buckman, Thompson, Cooper, Öpik, Koslowski, and others. Their investigations have revealed the pitfalls of homoeomorphy and polyphyletic development, pitfalls that trapped earlier workers who made identifications on the basis of external form alone. The lessons taught by these modern studies have not yet been applied to the Cambrian inarticulates. . . . No wonder Cambrian correlations based on evidence from brachiopods, especially the inarticulates, are regarded in some quarters as of doubtful value."

In a later paper (1944, p. 144) he refers to "the chaotic genera '*Obolus*,' '*Lingulella*,' and '*Lingulepsis*.' "

In contrast with these faunal elements of dubious stratigraphic value, typical faunas with *Hyolithellus* and diagnostic trilobites prove that Lower Cambrian rocks are present beneath the Deepkill shales. They are conspicuous in Troy (Troy quadrangle), on Ashley Hill (Kinderhook quadrangle), and along the Hudson River from Schodack Landing to the excellent exposures along U. S. Route 9J and the adjoining railway cut (Coxsackie quadrangle). It is probable that some Lower Cambrian crops out in the belt separating these exposures, as would be expected in a complexly folded terrane. Dale (1904) mapped several Lower Cambrian fossil localities in the northern part of the Kinderhook quadrangle but did not present his fossil evidence.

Structural Geology

Small-Scale Features

General.—Interpretation of the regional structure on the basis of relations in disconnected exposures is unreliable. The broad structural pattern is best determined from the map relations of the major units and careful study of a few critical exposures. Nonetheless certain structural features are worthy of mention because they may prove locally useful and may provide an insight into the tectonic history.

Primary features.—Intense metamorphism is as disastrous to primary features as to fossils; consequently, these original structures are not generally observed in the rocks of the eastern sequence. To the west, though, some outcrops exhibit criteria for determining top and bottom of beds.

Of these features cross-bedding is the most common and usually the most reliable. The limestones of the interbedded shale and limestone unit in the Deepkill are locally sandy; on weathering many of these beds reveal excellent cross-bedding. The interbedded shale and quartzite unit may contain very fine cross-bedding in the thin quartzites. Weathering also brings out the same feature on some of the sandy Canadian dolomites.

Ripple marks in the thin quartzites of the upper Deepkill and in the Austin Glen graywacke beds are not generally well enough developed to be useful. The basal red shale of the Normanskill contains infrequent groove casts and problematic small pits which have proved helpful. The Deepkill shales just above the falls at Stuyvesant Falls contain poorly developed impressions vaguely resembling raindrop marks.

Folding.—Throughout the quadrangle, wherever bedding can be determined, the rocks are folded. No uniform decrease in the intensity of folding from east to west could be traced across the quadrangle; rather the nature of the folding seems to be more closely related to the competency of the unit involved and the proximity of thrust faults.

The shale units, which constitute the bulk of the bedrock in the quadrangle, are readily deformed. In outcrops of shale alone the wave lengths are generally less than a few feet, but where interbeds of thin quartzite occur folds measuring 30 feet from crest to crest have been observed. Asymmetric folds are the most common, but overturned folds are not unusual. Particularly severe deformation may produce a "glazed" surface on the shales, especially near thrust faults.

In sharp contrast, however, is the behavior of the massive, more competent limestones, limestone conglomerates, quartzites, and graywackes. The folds in these units are the same shape as those in the shale—asymmetric and in some cases overturned—but they are of a much greater scale. This marked difference in relative competency of beds makes disharmonious folding inevitable, and tectonic unconformity between the shales and the massive units is evident where exposures permit detailed observation. While asymmetry of folding is the rule even among these massive units, simple symmetrical flexures are also known. Some representative folds observed are illustrated in Figure 6.

Faulting.—In most large exposures of dominantly shale sequences, thrusts are scattered through the folded beds. Such thrusts can be observed in the falls at Stuyvesant Falls (W17N8E) and in the gorge of Kinderhook Creek below the bridge at Valatie (W3S4E). These faults are generally stretch thrusts—*i.e.*, formed by stretching and shearing off of the forelimb. The thrust planes dip 20°–30°E., and the movement is usually measured in tens of feet.

Such thrust faults were not observed in the massive, competent strata though they may be present there as well. Many of the seemingly isolated quartzite exposures in the green slate terrane may have originated from thrust faulting.

The only normal fault known in the Kinderhook quadrangle occurs in a bed of massive green quartzite located in a streambed 1¼ miles southwest of Red Rock (E7N14W). It is a vertical strike fault, and the vertical slickensides indicate that the northwest side moved relatively down. The throw is apparently less than 20 feet, but it has been enough to form a scenic waterfall at the head of this valley.

Striations.—Striations are found in a few outcrops and are of two origins. In the quarry at Mt. Ida (SW8N10E) the Silurian-Devonian limestone is warped into gentle folds, the axes of which strike about N.15°E. Within the limestone strata the bedding planes bear numerous striations which trend about N.65°W. This feature is best developed on the abundant white calcite veins parallel to the bedding; it is clearly bedding-plane slippage formed between competent beds during folding.

The second type of striation is that associated with the many small thrust faults. Below the bridge over Kinderhook Creek at Valatie (W3S4E) is a folded series which illustrates well the development of these thrusts and striations. The fold axes strike N.15°–20°E.; the striations trend N.65°–75°W. and plunge gently eastward down the thrust planes.

Half a mile southwest of Arnolds Mill on the Kline Kill (C4N10W) green slate is exposed within a few hundred feet of the Chatham thrust, which is believed to be a major struc-

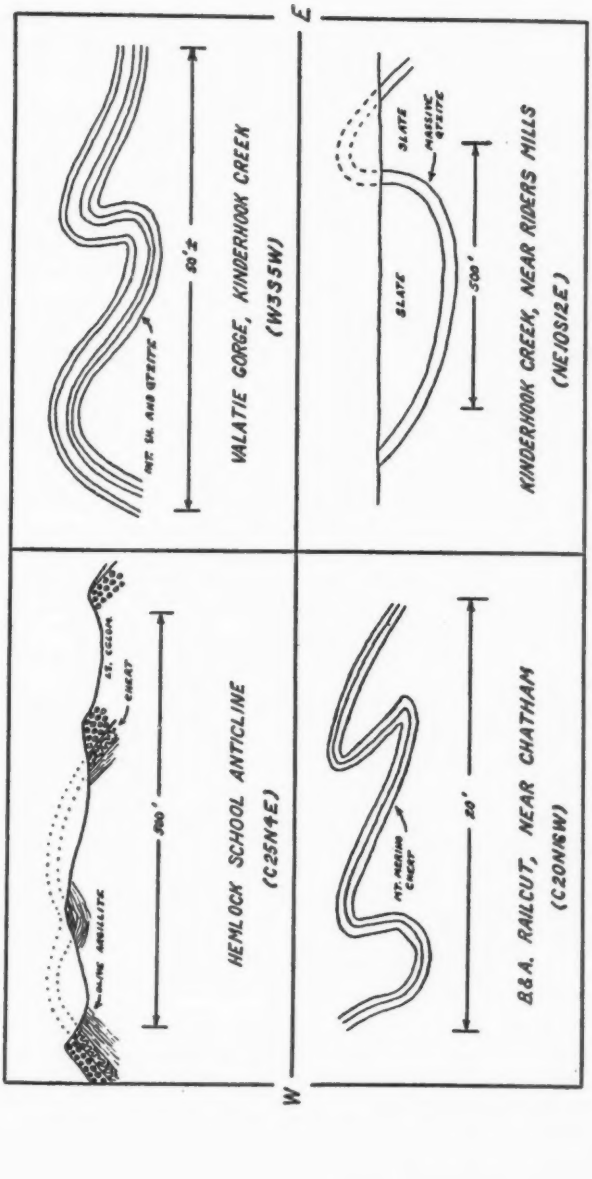

FIGURE 6.—SKETCHES OF SOME TYPICAL FOLDS IN ROCKS OF THE KINDERHOOK QUADRANGLE

tural discordance. The slates here are crossed by innumerable fractures, all heavily slickensided, and show definite evidence of having tendency toward cleavage. Where strongly developed it may obscure the bedding in shales, and separation of cleavage from bedding at

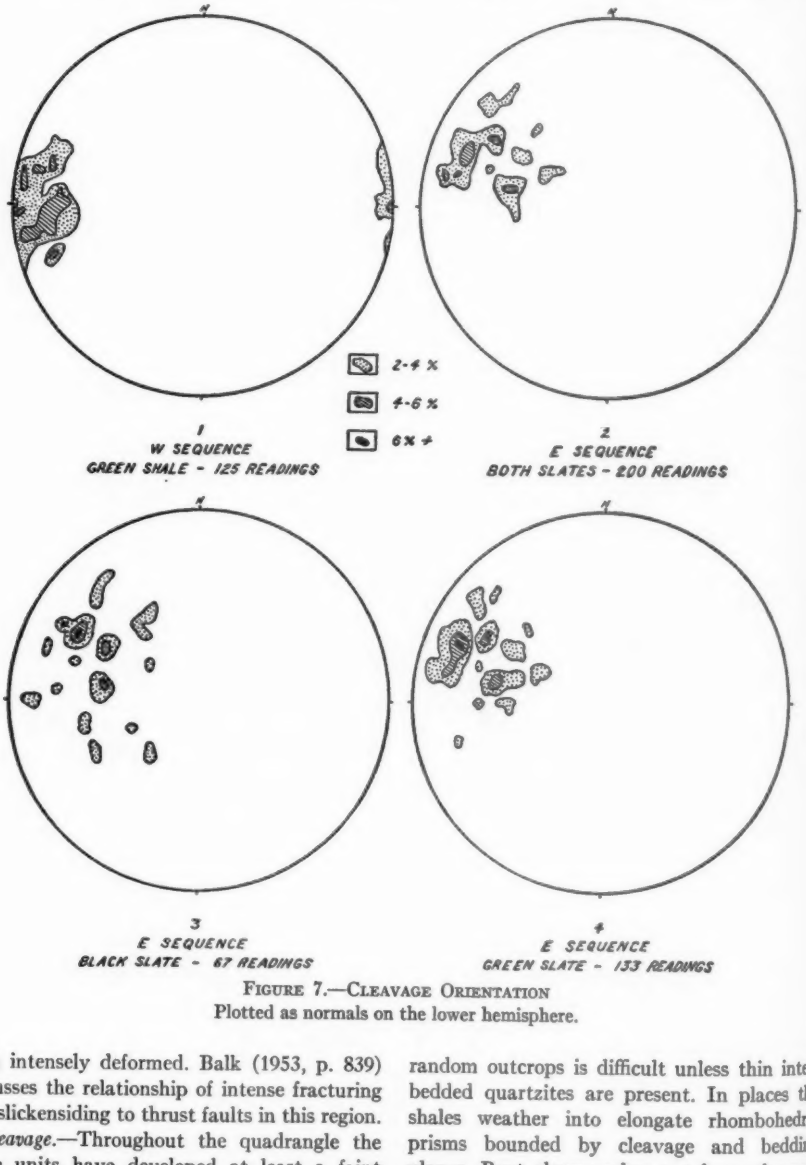

FIGURE 7.—CLEAVAGE ORIENTATION
Plotted as normals on the lower hemisphere.

been intensely deformed. Balk (1953, p. 839) discusses the relationship of intense fracturing and slickensiding to thrust faults in this region.

Cleavage.—Throughout the quadrangle the shale units have developed at least a faint cleavage; this cleavage becomes more pronounced eastward where even some of the massive quartzites and limestones show a faint

random outcrops is difficult unless thin interbedded quartzites are present. In places the shales weather into elongate rhombohedral prisms bounded by cleavage and bedding planes. Bent cleavage has not been observed except where associated with small thrusts.

During the field work, 325 cleavage readings were obtained, and these have been plotted

in Figure 7. The readings on opposite sides of the Chatham thrust differ distinctly in orientation, and this difference is even more apparent in the field. The mean reading for cleavages west of the thrust is strike due north, dip 74°E.; to the east this figure changes to N.18°E., 59°E. Plotting of these readings on the map reveals a surprising distribution from north to south. Near the northern edge of the quadrangle the readings on opposite sides of the thrust show little or no variation; but as the fault is traced southward, this difference of orientation increases and becomes extreme near the south border of the quadrangle.

Analysis of the readings east of the thrust reveals that the Lower Cambrian green slate shows a much more concentrated distribution of readings than does the Trentonian black slate. The Lower Cambrian beds were at least moderately deformed before deposition of the black slate; accordingly, one might expect the distribution of readings to be more random in the green slates than in the younger black slates which have been subjected to fewer cycles of deformation. That the opposite is true probably reflects the stabilizing effect of the massive quartzites that are distributed through the green slates and absent in the younger slates.

Pepper (1934) studied the cleavage readings in the Devonian shales west of the Hudson River and in the older "Hudson River beds," concluding that N.10°E. is the strike of Taconic cleavage while the later Appalachian cleavage averages N.25°–30°E. These trends are comparable to those in the western and eastern sequences respectively (Fig. 7), but the effects of the several post-Ordovician disturbances cannot be distinguished in the Kinderhook quadrangle.

Large-Scale Features

Unconformities.—Several unconformities can be inferred from exposures and map relations of the rock units in the quadrangle. As they are believed to have played a more prominent role in the history of the region than is generally acknowledged, these relations are summarized here:

(1) The angular unconformity between Upper Silurian limestones and folded shales (Deepkill?) is strikingly exhibited in the quarry at Mount Ida (Pl. 3, Fig. 2). This is the classic unconformity of the Hudson River region, displayed conspicuously from Kingston to Becraft Mountain.

(2) No exposure in the Kinderhook quadrangle proves the existence of the unconformity below the Trentonian black shale but its presence is inferred from the lack of beds known to be younger than Lower Cambrian below the black slate, the map relations of the black slate and older units, and the presence of this unconformity just to the south in the Copake quadrangle.

Near the eastern margin of the Catskill quadrangle the Trentonian black slate,[2] entering the map area from the east, rests on the Normanskill shale with a limestone pebble conglomerate at its base (mapped as "Rysedorph conglomerate" by Ruedemann). In the Copake quadrangle it lies on members of the carbonate series (Upper Cambrian to middle Canadian) and on the Lower (or possibly Upper) Cambrian gray-green slates. In the Kinderhook quadrangle it rests on Lower Cambrian slates and quartzites.

(3) The Deepkill may likewise rest unconformably on older strata, but compelling evidence is lacking in this quadrangle. Should the problematic limestone, shales, and limestone conglomerates on the hilltop 1 mile south of Ashley Hill prove to be Deepkill, their proximity to Lower Cambrian strata would imply a transgression of Deepkill seas across a surface of Lower Cambrian beds. Furthermore, the occurrence of Lower Cambrian fossils in the shale-and-quartzite lithology common to both Lower Cambrian and Deepkill beds suggests that Lower Cambrian rocks appear locally below the Deepkill in the western sequence.

If the green slate is Lower Cambrian, then the middle Canadian carbonate rocks along the Chatham thrust rest unconformably upon the Lower Cambrian green slate. The absence of the Canadian carbonate sequence west of the Chatham thrust suggests that pre-Deepkill

[2] This part of the black shale area is shown on Ruedemann's map as metamorphosed Normanskill, largely concealed by glacial drift. It is the direct continuation of the western Trentonian black slate belt of the Copake quadrangle (proven there by fossils) and exposes a calcareous zone with Trentonian fossils at its base.

erosion has removed the Upper Cambrian and Canadian carbonate rocks from much of the region. This interpretation also fits in well with the abundance of limestone conglomerates in the Deepkill.

The writer has already rejected, on purely lithologic grounds, Weaver's (1953, Ph.D. thesis, Univ. of London) interpretation of these slates as Upper Cambrian and Canadian in the Copake region. The fact that the assumption of an Early Cambrian age makes possible a simple explanation of the areal relations of the carbonate and Deepkill sequences is additional reason for the opinion that beds of Middle Cambrian, Late Cambrian, and early Canadian age are lacking in the Kinderhook quadrangle. This opinion cannot, however, be considered proven as it is ultimately based on the absence of faunas of these ages.

Folding.—The distribution of the Rensselaer graywacke outcrop areas in the eastern sequence, more or less surrounded by outcrops of the massive quartzites, suggests large-scale folding of this sequence. These outcrop areas are interpreted as centers of northeasterly striking anticlinal axes. One such axis trends through Old Chatham and Brainard, though the graywacke is not everywhere at the surface along this line; another axis is exposed in the Austerlitz outcrop area. Between these roughly parallel axes a structural low exposes Trentonian slate. The areal relations suggest that these folds were formed in the early Trentonian by moderate deformation that affected much of this region. Following this relatively gentle folding, erosion was extensive in the region (as shown by the various stratigraphic units that underlie the Trentonian black slate); a topography of low relief must have developed. As the Rensselaer graywacke stands as an upland (Rensselaer plateau) today, it probably also did during the development of this earlier topography. The transgressing middle Trentonian seas invaded the valleys and gradually covered these ancient hills with a thick black argillite. The present outcrop pattern of the black slate is believed due, therefore, to its preservation—after later folding and erosion—in the ancient topographic depressions where it was originally thickest. The main Taconian deformation in late Ordovician time accentuated this earlier folding and thrust the eastern sequence westward, possibly several miles in the southern part of the quadrangle, into its present position.

Large-scale folding of the western sequence is evident from the map pattern of the Normanskill synclinal remnants. Some areas show signs of small-scale thrust faulting, but these faults are believed to be incidental and subsequent to the folding. The areal pattern in the western sequence is basically one of folding, and the thrusts introduce only local complications.

The exact dating of this folding is complicated by a lack of detailed mapping in critical adjacent areas. The unconformity at Mount Ida proves that it is pre-Late Silurian. The folding of the rocks of the "Hudson River group" is generally dated as Taconian (late Ordovician). Fowler (1950, p. 35–37) and Weaver (1953, Ph.D. thesis, Univ. of London), however, have shown that a major unconformity exists below the middle Trentonian black slate. Therefore this folding may have taken place before the middle Trentonian. This unconformity, though apparently very widespread, has not been generally recognized until recently. Hence, an analysis at this date must be based largely on information from the Catskill, Copake, and Kinderhook quadrangles. Future investigations, especially in the southern Hudson valley, should do much to clarify this matter.

A great thickness of beds must have been stripped from the eastern sequence of the Kinderhook quadrangle to remove all the beds above the Lower Cambrian before the deposition of the middle Trentonian transgressive shale. Although considerable erosion unquestionably took place, the writer feels that some of the western sequence is absent in the eastern sequence because of nondeposition. In the western sequence, as far as can be inferred, the pre-middle Trentonian erosion cut down to at least the Mount Merino beds in the Catskill quadrangle. If the lone outcrop of black slate in the western sequence of the Kinderhook quadrangle is Trentonian, then the erosion evidently bared the Deepkill in places.

Thus some of this folding was definitely pre-middle Trentonian. However, the outcrop pattern of the Upper Cambrian-Canadian carbonate rocks in the eastern part of the Copake quadrangle, where they lie unconformably beneath the black slate, is one of moderate folding. It is not likely that the strata to the

west were more strongly deformed than those in the eastern part. Therefore, it is concluded that there was a moderate early Trentonian folding, but that the main folding was post-Trentonian and due to the deformation that also formed the Chatham thrust.

Thrust faulting.—Several minor thrusts have been drawn on the geologic map to explain anomalous relations between stratigraphic units. There is no indication of intense deformation or great movement on these thrusts, and they are considered minor structural features. With one exception there is little or no direct field evidence for these faults, but in view of the many known small-scale thrusts it seems most reasonable to explain these anomalous relations in this way.

Along the western edge of the westernmost Normanskill area in the quadrangle from Stockport southward the structural relations become obscure. Careful mapping shows the Austin Glen unit in a belt just east of the Deepkill beds along the edge of the quadrangle. These Deepkill beds are tightly folded and are vertical or dip very steeply. In a ravine on the east side of the creek half a mile north of Stottville (SW28S9E) the Normanskill beds (here containing considerable limestone) are thrown into a series of overturned folds, the limbs of which dip 45°–70°E. Beside the dam behind the old paper mill in Stockport (SW13S3E) wildly contorted Mount Merino beds overlie folded, but comparatively undeformed, Deepkill beds. On the ridge half a mile east of Stottville (SW26N11E) the Mount Merino shales and cherts show intense folding, and some of the shales have a glazed surface.

Critical exposures revealing the contact were not found. However, from these random outcrops the writer infers that the younger Austin Glen beds have been thrust westward over the Deepkill beds and have cut out the Mount Merino. Billings (1933) has discussed known cases of younger rocks thrust upon older, and a subsequent shear thrust seems the most likely explanation of this structure (Pl. 1).

The major structural discordance within the quadrangle is a thrust fault that extends from the southern border to near the northern and perhaps beyond; it is here referred to as the Chatham thrust as it passes directly through the village of that name. This thrust can be observed at four localities; its presence elsewhere is readily inferred from the condition and orientation of the rocks near its trace.

Just west of the road intersection three-quarters of a mile south of Riders Mills (NE22S6E) beds of massive green quartzite crop out in a pasture. These quartzites strike N.30°E.; the massive character of the rock makes dip readings uncertain. A few hundred feet to the west, at the base of the hill, typical Deepkill calcareous sandstone strikes N.5°E. and dips 80°E. The contact can be located more precisely about half a mile to the south along a dirt road (NE24S6E). Here the same Deepkill beds, striking due north and dipping about 70°E., crop out in the road. About 100 feet to the east in a rocky glen on the north side of the road the massive green quartzite strikes N.30°E. and dips 50°E. It is interbedded in tightly folded green slates.

On the west side of the hill a quarter of a mile northeast of the Rock City schoolhouse (E6S5E) Canadian carbonate rocks are exposed in a ravine, as described in the section on Stratigraphy. The carbonate rocks are thrown into a series of folds overturned toward the west; the fold axes trend about N.45°E. Beneath the contact with the carbonate rocks are crushed shales which weather very readily. About 100 feet to the west these shales strike due north and dip steeply east.

The thrust can also be observed at the carbonate rock knolls along the old Rutland Railroad tracks 1½ miles north of Chatham. Here the Canadian carbonate rocks strike about N.20°E. and dip 50°E. Fifty feet to the west in a pasture are severely folded Mount Merino shales with graptolite fragments. As at the previous locality, the shales directly beneath the thrust are pulverized.

The fourth locality is in the bed of the Stony Kill just below and downstream from the old Rutland Railroad trestle (C22N8W). To the west in the stream bed are Austin Glen graywacke beds which strike N.5°W. and dip 80°E. Fifty feet upstream to the east is the contact with the green slates, and the Austin Glen here strikes N.25°E. and dips 60°E. Just above the contact are phyllitic green slates in which the cleavage strikes N.45°E. and dips 35°E. An upstream traverse passes alternately through green slates and black slates, repeating the

cycle several times in a quarter of a mile. The intense folding together of these two slates is nowhere better illustrated than in this exposure.

In addition to these directly observable thrust relations, more subtle indications of thrusting are found in the field. Anomalous strike readings, such as due east, are commonly found just west of the thrust. The intense fracturing and slickensiding of the slates southwest of Arnolds Mills near the thrust have already been described.

The relations of the Lower Cambrian slate, the Canadian carbonate rocks, and the younger beds west of the thrust are for the most part rather obscure. However, the Canadian carbonate rocks appear to rest upon older slate and are not anticlinal. By analogy to the well-exposed structure at Bald Mountain, some 30 miles north in the same belt of slates, the structural origin of these separated limestone and dolomite outcrops is interpreted to be "slivering" along a thrust fault (Pl. 1). The gross structural plan in the quadrangle may be compared in many aspects to northern Vermont, where major thrusts divide the area into a number of "slices" in which the rocks grow progressively older eastward.

North of the village of Chatham, wherever the fault is visible, it seems to be dipping about 50°E. South of Chatham the fault disappears beneath glacial debris and emerges again for a short distance in the northwestern quarter of the Copake quadrangle (Weaver, 1953, Ph.D. thesis, Univ. of London, p. 102). At this point the thrust plane evidently dips very gently eastward. Thus the angle of dip apparently is fairly steep to the north but becomes more moderate to the south.

South of Rider Mills Lower Cambrian quartzites are thrust over Deepkill calcareous sandstones; the stratigraphic displacement on the thrust here is moderate, possibly a few hundred feet. Near the village of Chatham, however, the Lower Cambrian slates with massive quartzites rest upon Austin Glen graywacke. The stratigraphic displacement here apparently is at least 2000 feet. While generalizations from two exposures are dangerous, it seems that the displacement increases to the south. As was noted, the difference in cleavage orientation on opposite sides of the thrust also increases markedly toward the south. The Deepkill limestone conglomerates around Ghent strike into and seemingly under the trace of the thrust (Pl. 1).

The thrust cannot be dated accurately in the Kinderhook quadrangle, but in the Copake quadrangle green slate is thrust upon the black Trentonian slate. Thus the movement is post-middle Trentonian. As this thrusting is believed to have accompanied the deformation that folded the shales of the western sequence, it can be dated as probably late Ordovician (Taconian) on the basis of the Mount Ida unconformity; it may be younger.

The extent of this thrust has not been determined. Southward it extends at least into the Rhinebeck quadrangle (Weaver, 1953, Ph.D. thesis, Univ. of London, p. 102); it probably extends northward beyond the Kinderhook quadrangle as well. Ruedemann (1930, p. 151) has described suspected thrusting along the western edge of the Rensselaer plateau near Poestenkill. A line extended due south from this point passes along the west side of the North Nassau Rensselaer graywacke outcrop, along the west side of Curtis Mountain (composed of folded Lower Cambrian massive quartzites), and into the Kinderhook quadrangle close to the known trace of the Chatham thrust.

"*Window.*"—The "window" shown on the Tectonic Map of the United States (1944) within the area of the Kinderhook quadrangle was apparently drawn to account for the existence of limestone areas of "autochthonous" facies in the midst of a large "allochthonous" shale terrane. In the absence of detailed mapping, this device was consistent with the general hypothesis of the "Taconic klippe." The field relations of the scattered small limestone outcrops make their interpretation as "windows" in a thrust sheet highly improbable, if not impossible.

Discussion of the "Taconic Klippe"

Development of the Hypothesis

The concept of a large "klippe" of "allochthonous" clastic rocks resting in the Hudson River valley on top of a carbonate "autochthonous" series of time-equivalent sedimentary rocks seems to have developed gradually in the literature. In so far as the writer knows, it has

nowhere been stated systematically for the whole region.

The observations made in the Kinderhook quadrangle and in the adjoining Copake quadrangle led the writer and John Weaver, who had been introduced to the problem by Professor Bucher, to reasons of their own for questioning this far-reaching interpretation. The writer's doubt in this matter was strengthened by a careful study of the literature. An attempt is made to trace the development of the klippe hypothesis, to state clearly the premises on which it is based, and to examine critically these premises to determine if an alternative interpretation of the regional relations is possible. The historical summary shows how the conclusions reached may be integrated to make a consistent story—a story that stands or falls with the ultimate judgment of the interpretations on which it is based.

To assist in analyzing the logical steps that have led to the idea of the "Taconic klippe," a brief review of the development of the concept is presented.

One of the earliest references to large thrusts in this area is found in the writing of Dana (1886b). In discussing Taconic stratigraphy he mentioned that some persons had asked if a great overthrust might not be present, basing their reasoning on the juxtaposition of metamorphosed rocks and fossiliferous rocks and the analogy to the Scottish Highlands. While Dana dismissed the suggestion as having not "a shadow of evidence" in its favor, it is nonetheless of interest that visions of overthrusting had already appeared at this early date.

The first important suggestion of overthrusting was made by Keith (1912; 1913). His study of the north end of the Taconic Range in Vermont convinced him that the Cambrian slates of this range must rest with tectonic unconformity upon the Ordovician "Stockbridge" limestone.

Shortly thereafter Ruedemann (Cushing and Ruedemann, 1914, p. 99–115) described the Cambro-Ordovician shales of the Schuylerville quadrangle, to the east of Saratoga Springs, New York. He found evidence of two roughly parallel thrusts, which he considered to be major structural breaks. The thrusting resulted from the pressure of the heavy ocean basin, and he believed the overthrust shales originated some distance to the east.

The work of Berkey and Rice (1921) and E. B. Knopf (1927) developed the interpretation of the Fordham gneiss-Lowerre quartzite-Inwood limestone-Manhattan schist sequence on the east flank of the Hudson highlands as an overthrust precambrian terrane.

Ruedemann (1930, p. 130–151, 162–165), in studying the Capital district (Albany and environs), developed his theory of two separate sedimentary basins later brought together by large-scale thrusting. He quotes no estimated distance of movement but presumably was thinking in terms of a number of miles.

Keith (1932) first estimated the distances involved; he postulated that the sole of the thrust lies in the middle of the Green Mountains and that the shales had been moved westward about 20 miles.

Schuchert and Longwell (1932) in discussing the deformations of the Hudson valley accepted the hypothesis of the overthrusting of the "Hudson River group" into its present position, but recognized the problem of locating the southern boundary of this "eastern sequence."

In the same year Prindle and Knopf (1932) reported on the Precambrian and metamorphosed Paleozoic rocks of the Taconic quadrangle. Their interpretation of the structural features included two large-scale overthrusts and many alpine-type recumbent folds.

Keith (1933) elaborated on his earlier work and envisioned the northern Taconic Range as containing a number of allochthonous thrust slices.

In discussing the structure of the Whitehall quadrangle, New York, Rodgers (1937, p. 1580–1588) mapped the western border of the Taconic slates and suggested that they have been thrust westward some 20 miles from roots near Rutland, Vermont.

Kay (1937, Pl. 5) first drew the boundaries of the "Taconic klippe" and showed it on a palinspastic map as having originated about in the present vicinity of Boston. In later papers (1941; 1942, p. 1618) he extended the belt of Taconic thrusting southward into Pennsylvania and northward as far as Newfoundland, indicating minimum displacements of 30 miles in

Pennsylvania and 40 miles from New York northward.

Ruedemann (1942a) and Goldring (1943) continued the mapping of the Hudson valley shales, and their reports reiterated the overthrust nature of this belt of shales.

Later in 1942 Ruedemann published a short paper in which he abandoned the traditional concept of two separate sedimentary troughs and represented the carbonate and shale facies as marginal and central deposits in a single trough (Ruedemann, 1942d, p. 56–59, especially Fig. 9, p. 57).

E. B. Knopf accepted the representation of the Cambro-Ordovician shale sequence as the "Taconic klippe" on the Tectonic Map of the United States (1944), essentially along the lines outlined previously by Kay.

Cady (1945, p. 578–580) mapped the north end of the Taconic Range as the end of a klippe, the movement of which was placed at a minimum of 50 miles in the latitude of Albany. Kaiser (1945, p. 1094–1097) studied this same area in greater detail and also interpreted the Taconic sequence as overthrust, though he admitted that some of the relations were obscure.

Chadwick (1946) reviewed Ruedemann's paper on the Catskill quadrangle and considered the evidence for overthrusting convincing.

In an abstract E. B. Knopf (1946) discussed the relations around Stissing Mountain in the Lower Hudson valley and concluded that the phyllites had been thrust over the carbonate rocks, reaffirming her earlier interpretation.

The problematic lithologies found with probable Martinsburg shale in small areas of southeastern Pennsylvania were studied by Stose (1946) and considered a klippe with the same relationship to the "Martic thrust" as the "Taconic klippe" bears to the thrusting farther north.

Flower (1949) discussed the structural history of the Hudson valley; he considered the shales as having been thrust upon the carbonate rocks but deposited originally in the eastern part of the same basin. L. D. Bonham (1950, Ph.D. thesis, Univ. of Chicago) and Fowler (1950, p. 64–69) supported the "klippe" hypothesis in the Hoosick Falls, New York, and Castleton, Vermont, areas respectively.

P. B. King (1951, p. 98–100) adopted this hypothesis in his interpretation of Northern Appalachian structures.

Rodgers (1952) and Thompson (1952), in an excellent summary of the Taconic problem, reviewed the two alternative structural hypotheses and their respective shortcomings. They accepted (p. 11–12 and accompanying geologic map) the klippe hypothesis as the more probable, at least in explanation of the northern portion of the Taconic sequence.

Structural Considerations

From the imposing volume of literature on the subject cited above it would seem that by now the "Taconic klippe" would be completely mapped and sharply defined. It is surprising, therefore, to discover how few authors have published large-scale maps delineating the boundaries of the "klippe." It is more surprising to find that large areas within this "klippe" have been mapped only in reconnaissance, if at all.

These boundary problems cause serious doubts about the validity of the hypothesis. Along the western border the numerous thrust faults present allow several possibilities for the front of this "klippe," but closer examination reveals that none of these faults provides a satisfactory boundary.

Ruedemann (1930, p. 133–143) interpreted the western margin as a belt of numerous thrusts with insignificant individual throws but an important cumulative effect. Such a staggering of local thrusts is, of course, the exact opposite of the sole of a thrust mass that has been brought from the east across a score of miles. This contradiction made Bucher doubt the klippe concept and led to the detailed studies of John Weaver and the writer. Others have also recognized this difficulty (*e.g.*, Rodgers, 1952, p. 10).

An alternative for the "klippe front" is the so-called Logan's Line, a structural break that extends from the vicinity of Sudbury, Vermont, southward into New York where it continues along the east side of the Hudson River. Here, as well, structural anomalies all but exclude this as a possible boundary for the "klippe." Under this interpretation the Normanskill and Deepkill formations would lie both in the

"klippe" and in the autochthone directly beneath the thrust, thus effectively removing the main reason—the contrast of facies between beds of the same age in the autochthone and in the allochthone—for postulating the overthrust! Furthermore, this fault becomes indistinct to the south and apparently fades away in the Catskill quadrangle.

The problem is even more complicated along the eastern margin of the "klippe." In the few areas where the relations have been studied carefully the contact of the "Taconic sequence" and the "Valley sequence" is obscure—in most places shale against shale. The writer knows of no locality where older shale definitely rests upon younger limestone as would be expected if a true klippe were present.

At the north end of the Taconic Range in Vermont is the strongest structural evidence for the type of long-range thrusting implied in the klippe hypothesis. As the stratigraphic relations are interpreted at present, the klippe hypothesis explains the inferred structural relations well. On the other hand, the possible presence of long-range thrusting at this point is no guarantee that it continues southward over scores of miles; the crucial region lies near the southern end of the hypothetical klippe. But even at the northern end the "klippe" nature of the rocks involved is not proven. Definite thrusting is visible only along the western side of the "Taconic sequence." Along the north end and the eastern margin a problematic shale sequence obscures the pattern of outcrop. Kaiser (1945, p. 1095), who has done the most detailed work in this critical area, states that the structural evidence here is not decisive.

Toward the south it becomes difficult to determine just where to end the "klippe." Schuchert and Longwell (1932, p. 305) recognized this problem and suggested that it probably "dies out" in New Jersey. However, Stose (1946) has described rocks remarkably similar in lithology and succession to the "Taconic sequence," and the "klippe" problem apparently reappears in southeastern Pennsylvania.

The gross uncertainty over the boundaries of the "klippe" constitutes the strongest structural argument against it. In addition the severe deformation commonly associated with extensive overthrusting is in many places lacking in these rocks, especially near the margins of the "klippe." It has been shown, however, that large overthrusts may be present with very little structural evidence of their existence (Knopf, 1935).

Recent work by Hawkes (1941), Osberg (1952), and Brace (1953) in Vermont has left the root zone of the Taconic thrust still undetected. This is not potent evidence against the overthrust hypothesis, however, as detailed studies in central Vermont are greatly hampered by the intense metamorphism and the uncertainty of stratigraphic relations. Furthermore, Cady (1945, p. 578–579), Rodgers (1952, p. 12–13), and Thompson (1952, p. 20) have suggested that flowage down a topographic gradient may be the mechanism by which the "klippe" was emplaced; accordingly, it may be argued that the thrust need have no root zone.

Stratigraphic Considerations

Introduction.—The concept of the "Taconic klippe" has developed primarily because of seeming incongruities of regional stratigraphy; structural evidence for its existence is slight and far from compelling. Previous workers have referred to two Cambro-Ordovician sequences, the "Taconic" argillite sequence and the surrounding "Valley" carbonate sequence. These two sequences are generally considered of equivalent age and mutually exclusive, and it is mainly their juxtaposition and the seeming impossibility of such abrupt facies changes that have fostered the growth of the klippe hypothesis.

Any critical review of the "klippe", therefore, must examine this stratigraphic evidence in detail, and any attempt to deny the existence of such a klippe must offer a satisfactory alternative interpretation of the stratigraphic relations.

The validity of the stratigraphic argument for the "klippe" is, of course, directly dependent on the accuracy of correlation between the lesser rock units in the two Cambro-Ordovician sequences. Accordingly the stratigraphy of each epoch of these two periods will be discussed with special regard for the problems of facies change and correlation. The most effective method in such an analysis is to begin with the

youngest strata involved and mentally "lift off" the map each unit in proceeding to discussion of the older units.

Trentonian.—The Trentonian rocks are the youngest known either in the Kinderhook quadrangle or elsewhere in the "Taconic klippe." Kay (1937) has studied the Trenton group of the Mohawk valley in detail, and his classification is followed here.

The Trentonian is represented in the Kinderhook quadrangle by the black slate of the eastern sequence and by two outcrops of what is believed to be the basal limestone in the extreme southeast corner. Some of the small limestone areas in the string of outcrops along the Chatham thrust may hold bits of infolded Trentonian limestone as dated by Bishop (1886; 1890)—in this case presumably representing erosional remnants. The Trentonian rocks are believed to rest with unconformity on the Lower Cambrian green slate and possibly on rocks as young as Canadian (carbonate rock) or Chazyan (Deepkill).

Immediately to the south in the Copake quadrangle the Trentonian black slate bearing fossils suggesting a Snake Hill age, and its sporadically developed basal limestone lie uncomformably on beds of Late Cambrian and Canadian age (Weaver, 1957) and, according to the writer's interpretation, on Lower Cambrian rocks as well.

Where the western belt of black slate, which has also yielded Trentonian fossils, crosses from the western border into the adjoining Catskill quadrangle, it exhibits locally a limestone conglomerate with a Trentonian fauna in the matrix. This conglomerate, which Ruedemann mapped as Rysedorph conglomerate, lies on Normanskill shale.[3]

The southward continuation of this Trentonian slate and limestone is only sketchily known; however, data are sufficient to establish its continuity, though it has in the past merely been mapped with older shales as "Hudson River shale." This same combination of black slate with a locally developed basal limestone (in places a limestone conglomerate) has been found in the Millbrook quadrangle (Knopf, 1927, p. 439–441), the Rhinebeck quadrangle (Warthin, 1949), the Poughkeepsie quadrangle (Dale, 1879; Gordon, 1911, p. 48–96), the Newburgh quadrangle (Holzwasser, 1926, p. 36–65), and south as far as Peekskill (Bucher, 1951). D. W. Fisher of the New York State Museum (Personal communication) has suggested the correlation of this basal limestone (locally a limestone conglomerate), here known as the Balmville, with the Rysedorph conglomerate to the north and with the Kirkfield of the standard section to the northwest.

In southern New York Leonard Larsen (1953, M. A. thesis, Columbia Univ.) found a thin limestone at the base of the Martinsburg black slate. This limestone, which he correlated with the Balmville, lies unconformably on the Kittatinny carbonate rocks (Canadian and older). Lewis and Kummel (1931; 1940, p. 74–76) indicate that this same general relationship exists from New York to Pennsylvania.

Miller (1937) studied this basal limestone (Jacksonburg) in New Jersey and eastern Pennsylvania, and found it unconformably above the Kittatinny and overlain with slight unconformity by the Martinsburg. He correlated the Jacksonburg with the Rockland, Hull, and Sherman Fall of the standard section. Willard (1943) put the Martinsburg in the lower Trentonian and higher; he also found it was underlain by a Trentonian limestone in eastern Pennsylvania. Stose and Jonas (1939. p. 77–80) report the Martinsburg shale with a thin basal limestone resting unconformably upon the Beekmantown limestone in south-central Pennsylvania. Cooper and Cooper (1946, p. 92) have suggested a similar unconformity below the Martinsburg and its basal limestone as far south as Virginia, though it is not so positively developed there.

Along the Hudson River and to the west in the Mohawk valley the middle Trentonian is represented by the Canajoharie, Snake Hill, and Schenectady shales which coarsen upward and eastward and pass into limestones westward (Ruedemann, 1930, p. 29–37, 117–123; Kay, 1937, p. 268–274; 1942, p. 1607–1614; 1953, p. 53–64). Fisher (1954, p. 77) has recently emphasized the presence of an important unconformity between Trentonian rocks with a

[3] Ruedemann (1942a) considered the associated black slates as Mount Merino, but Chadwick (1946) called attention to the unconformable nature of these black slates and the associated limestone conglomerate. Weaver (1957) has demonstrated their areal continuity with the Trentonian slate.

few feet of Lowville limestone at their base and the older Cambro-Ordovician carbonate rocks, the highest beds of which are Canadian. Northward this Trentonian shale and limestone sequence is traceable along the front of the Adirondacks and into the Champlain valley (Cushing and Ruedemann, 1914, p. 45–53; N. Y. State Geological Association, 1951, p. 16; Rodgers, 1952, p. 33).

North of the Kinderhook quadrangle the Trentonian has been recognized in the Troy quadrangle (Ruedemann, 1930, p. 104–113) as the Rysedorph conglomerate. The shales associated with this conglomerate apparently have not been areally separated from the Mount Merino beds of the vicinity. Dale (1893, p. 306) mentions a mass of black slate 600 feet across well inside the borders of the Rensselaer plateau; he suggests that it may correlate with the "Berkshire schist" to the east (at least some of which is Trentonian). In his paper on the slate belt, Dale (1899, p. 190) mentions "Trenton" limestone occurring sporadically through the Ordocivian sectors of the belt. Near the end of the Taconic Range in Vermont the Hortonville slate and a basal limestone unit lie unconformably upon older carbonate rocks (Cady, 1945, p. 559-560; p. 31-37). Keith (1932) first correlated the Hortonville and the Snake Hill shale.

Though severe metamorphism has complicated stratigraphic work, the results of Dresser (1925), Currier and Jahns (1941), and Osberg (1952) suggest that this Trentonian black slate with a basal conglomerate may be present east of the Green Mountains in Vermont and Quebec.

The extent of the Trentonian rocks east of the Kinderhook quadrangle is rather speculative. Weaver (1957) has shown that the Berkshire schist along the eastern margin of the Copake quadrangle is metamorphosed Trentonian black slate. Studies by Agar (1929; 1932; 1933), Balk (1936), Dale (1920; 1923), and Moore (1935) strongly suggest that many of the schists of western Massachusetts and Connecticut may be the metamorphosed transgressing Trentonian shale; many of the unusual map patterns ascribed here as elsewhere in the region to faulting might well be re-examined for the alternative possibility of unconformity.

Just east of the Kinderhook quadrangle Ford and Dwight (1886) found "Trenton" limestone at Canaan, New York. There can be little doubt that the Trentonian black slate in the Kinderhook quadrangle is the same unit that Prindle and Knopf (1932, p. 268–269) mapped as Walloomsac slate. From their map, the map by Balk (1953, Pl. 1), and reconnaissance in the intervening area, the two belts can be traced into one another. Prindle and Knopf correlated the Walloomsac with the Normanskill on the presence of "*Diplograptus foliaceous*;" from the loose usage of this name (Ruedemann, 1947, p. 416–419) it cannot be considered an obstacle to considering these rocks as Trentonian. The Walloomsac is here underlain by a "crinoidal" limestone. North of the Taconic quadrangle is a gap of about 35 miles to Fowler's map (1950) for which the only available geologic map is that of Dale (1899); he indicates the presence of "Berkshire schist" along the east side of the slate belt.

Though mapping is far from complete in this region, from Vermont to Pennsylvania the older rocks of this lowland apparently are overlain unconformably by a locally developed lower Trentonian limestone or limestone conglomerate at the base of a middle Trentonian black shale, slate, or schist.

In tracing this black slate with respect to the boundaries of the "Taconic klippe" a most remarkable situation develops. In southeastern Pennsylvania the Martinsburg can be traced westward into the folded Appalachians and rests everywhere in its normal stratigraphic position. To the writer's knowledge there is no one who suggests that the Martinsburg here is part of any "klippe," excluding Stose's (1946, p. 678–696) "Hamburg klippe" which is another matter entirely. But in tracing the Martinsburg northward through New Jersey into New York, somewhere along this belt one crosses from the "autochthonous" slates to those of the "Taconic klippe" east of the Hudson River. As the belt continues northward, it lies in this "klippe" in the Copake and Kinderhook quadrangles but suddenly crosses back into the "autochthonous Valley sequence" in the Taconic quadrangle. To the north the Trentonian slate apparently remains in this "Valley sequence" (Cady, 1945; Fowler, 1950).

In the southern area no evidence has been

found for drawing the southern boundary of a klippe through the Trentonian slates. Furthermore, in comparing the geologic map in this report (Pl. 1) with those of Prindle and Knopf (1932) and Balk (1953) it is seen that the black slate belt of the Copake and Kinderhook quadrangles trends directly into the slate belt in the Taconic quadrangle, where the map relations of the other stratigraphic units are also comparable. Reconnaissance mapping in the Pittsfield quadrangle shows that this belt is continuous.

The implications of the continuity of this important belt of black slate should not be underestimated. Possibly, of course, major thrusts might pass through these slates and remain undetected, but the similarity of lithology, the parallel geologic relations, and the regularity of the contacts make such a relationship improbable.

If this belt is continuous, this formation cuts indiscriminately across both "autochthonous" and "allochthonous" sequences. It seems reasonable, therefore, to infer that this Trentonian black slate is not involved in any "klippe" but is a transgressing sequence now overlying the rocks upon which it was originally deposited. It also follows that if there is any "klippe", it must have been formed before the early Trentonian and can include only older beds.

Bolarian and Chazyan.—Before discussing the distribution of rocks in these two groups it is necessary to establish the correlation between the standard Ordovician limestone section of the Mohawk and Champlain valleys and the argillite section in the "Taconic sequence."

Since its original definition as a formation by Ruedemann, the Normanskill has been correlated through a wide range in the limestone standard section. Ruedemann originally placed the Normanskill in the Trentonian, but Ulrich insisted that both the Normanskill and its southern equivalent, the Athens shale, were properly included in the Chazyan. Later Ruedemann (1942a) lowered the Normanskill into the Bolarian and Chazyan. Cooper and Cooper (1946) correlated their new Edinburg formation with the Normanskill and with the Black River and possibly lower Trenton of the New York limestone section. Most recently Decker (1951; 1952) completed the cycle by elevating the Normanskill once again into the Trentonian. The writer accepts the correlation of Cooper and Cooper since thick unconformable Trentonian black slate of this region shows that a large part of the Trentonian must be later than the Normanskill.

The correlation of the Deepkill shale, which underlies the Normanskill with apparent conformity, has been, on the whole, more constant. Ruedemann (1902) correlated it with the Beekmantown, and since that time many have considered the Deepkill and the Canadian essentially equivalent. Apparently Lapworth, when he originally studied the Quebec faunas, put the beds equivalent to the middle Deepkill in the Chazyan; later he decided they were older and called them Lower Ordovician. Walcott (1890) studied the Levis conglomerates and assembled a fauna of brachiopods, gastropods, and trilobites from the matrix of the beds. Principally on the basis of these forms the lower and middle Deepkill were correlated with the Beekmantown and possibly the lower Chazy. Ruedemann, however, quotes Walcott as having found the middle Deepkill in Nevada in rocks that were assigned to the Chazyan.

Ruedemann (1921, p. 130) showed the upper Deepkill as equivalent to the middle Chazy on his correlation table. In subsequent papers, however, he correlated the Deepkill with the Beekmantown and lower Chazy (1930, p. 95) and again with the Beekmantown and possibly lower Chazy (1942a, p. 180).

Thus even from the start there has been uncertainty over the exact position of the Deepkill and Levis formations with respect to the standard limestone section. Rasetti (1946, p. 704) reviewed the correlations in Quebec and referred to the "upper Canadian Levis formation"; moreover, he points out the similarity of the situation in eastern New York and the fact that the "fossils of the formation in Washington County are far more abundant than in the rocks here discussed."

Decker and Merrit (1931) and Decker (1935) in studying the Simpson group of Oklahoma found middle Deepkill graptolites in the Joins (basal Chazyan). Ruedemann

(Decker and Merrit, 1931, p. 15), in a letter concerning this fauna notes:

> "... So you see the occurrence of *D.* (*Didymograptus*) *artus* may not contradict the other faunules as much as it would appear at first sight. It may actually be here a Chazy form and not a Beekmantown form."

Decker (1936) reports the occurrence of *Phyllograptus anna*, a supposedly middle Deepkill graptolite, 1000 feet below *Didymograptus bifidus*, another middle Deepkill graptolite. Thus in Oklahoma at least the individual species apparently occur at different stratigraphic levels or over longer ranges than in the type section of the Deepkill.

Dunbar (1954, p. 255–256) has summarized the results of work in western Newfoundland and has emphasized the significance of these findings in establishing the age of the Deepkill fauna. The richly fossiliferous Table Head limestone grades upward through transitional beds into black graptolite-bearing shales; its fauna and unconformable relationship to the underlying Canadian dolomite leave little doubt that this limestone is Chazyan. Yet the overlying shales contain several graptolite genera, two of which (*Phyllograptus and Tetragraptus*) occur in definite zones in the Deepkill type section. Evidently either these graptolite genera have a considerably longer range than heretofore believed, or the original correlation of the Deepkill shale with the Canadian may be in error.

However, since the graptolite faunas alone do not yield decisive results, another approach is desirable. Ross (1948, Master's thesis, Cornell Univ. 1949) studied microscopically the pebbles of the conglomerates in the type section of the Deepkill and compared these pebbles to the formations of the standard carbonate rock section in eastern New York. Her results suggest that much of the Deepkill is actually not Canadian, but Chazyan. The upper conglomerates of the type section must be high in the Chazyan as they contain pebbles considered lithologically diagnostic of the middle Chazy Crown Point limestone. The Deepkill thus may be uppermost Canadian and Chazyan.

Below the Deepkill in the Capital district Ruedemann (1930, p. 85–86) lists the Schaghticoke formation which crops out only in the town of that name and possibly at a few other scattered localities. The designation of these beds as a separate formation is made on a purely paleontological basis—*i.e.*, the presence of *Dictyonema flabelliforme* v. *acadicum*, *Staurograptus dichotomus*, and *Clonograptus* cf. *milesi*. In this respect Decker's (1945, p. 19) chart shows that the relation of these stratigraphically low forms in northeastern North America to similar graptolite faunas and to the limestone section is weakly established as these species (except *Dictyonema flabelliforme*) have a limited geographic distribution. The genus *Dictyonema* extends to the Mississippian, the genus *Staurograptus* is found in the Lower Ordovician of Australia, and *Clonograptus* occurs 30 feet below *Phyllograptus typus*, a lower Deepkill form, at Levis, Quebec (Raymond, 1914).

The faunas of these lowest Deepkill horizons have been found only in the limited area between the type locality of the Schaghticoke and the Cherry Hill locality in the Catskill quadrangle. Quite possibly in a small area within the carbonate basin shale deposition started earlier, and these horizons may be time equivalents of the lower and middle Canadian carbonate rocks. More detailed stratigraphic and faunal studies are needed.

If the above correlations are permissible as a working hypothesis, the next step is to analyze the distribution of the Bolarian and Chazyan limestones and the Normanskill and Deepkill shales. These two facies appear to be geographically separate; the limestones occur to the northwest, and the shales to the southeast.

Black River limestone has been reported from the eastern Mohawk valley (Cummings and Prosser, 1900, p. 423–424), but more recent studies (Young, 1943; Fisher, 1954, p. 77–79) indicate that it is here represented by only a few feet of Lowville limestone. The Chazy limestone is absent in this area. The Black River section is well developed in the western Mohawk valley.

In the lower Champlain valley Black River limestone has also been described in the past, but these rocks are now assigned to the Trenton (N. Y. State Geological Association, 1951, p. 16). The Chazy is about 700 feet thick but thins southward and disappears (Rodgers,

1937, p. 1579). In west-central Vermont (Cady, 1945, p. 548–555) the Bolarian does not seem to be represented, and the Chazyan limestone becomes argillaceous to the east. Along the east side of the "klippe" no undoubted Bolarian or Chazyan limestone is known. Dana (1877, p. 337–339) quotes Wing as having found Chazyan limestone at West Rutland, but the evidence rests solely on gastropods and a cystoid plate. Prindle and Knopf (1932, p. 274) mention both Black River and Chazy limestones in the Taconic quadrangle, but the former is almost certainly the basal limestone of the Trentonian black shale, and the fossils in the latter are too fragmentary to be considered reliable. Southward no Bolarian or Chazyan limestones are known.

The precise extent of the Normanskill and Deepkill outcrops within the region is unknown owing to the lack of modern geologic mapping over considerable areas. Normanskill beds have been reported as far north as the Castleton quadrangle (Fowler, 1950, p. 55–57) and extend scattered through the Taconic Range and the Hudson valley as far south as Poughkeepsie (Gordon, 1911, p. 82–96). West of this belt they are generally covered by younger shales, and their extent eastward is masked by metamorphism.

The extent of the Deepkill is known only in general. Ruedemann (1947, p. 63) reports it as far north as Washington County, New York. In the same belt as the Normanskill it continues southward intermittently as far as the Rhinebeck quadrangle (Warthin, 1949).

The Normanskill has been reported in New Jersey (Lewis and Kummel, 1940, p. 73), and the Deepkill and Normanskill in the "Hamburg klippe" of Pennsylvania (Stose, 1946). The Edinburg formation, with the Normanskill graptolite fauna, occurs in the Shenandoah valley of Virginia (Cooper and Cooper, 1946).

The mutual exclusiveness of the limestones and shales of the Bolarian and Chazyan is unmistakable. Of course certain areas, especially southeastern Pennsylvania, seem to show limestones and shales of comparable age lying very close to one another. However, this cannot be used as an argument for thrusting, until the possibility of a zone of interfingering facies is fully explored. Cooper (1945) has shown that the term "Stones River" has been applied to beds of quite different ages; accordingly, the Stones River limestone near the "Hamburg klippe" must be dated precisely, and its relation to the shales within the "klippe" must be studied before this critical area can be considered as evidence either for or against far-travelled overthrusts.

In Virginia, however, the relations of the shales to the limestones have become clear through the excellent study of Cooper and Cooper (1946). They have divided the Edinburg formation (equivalent to the Normanskill) into a northwestern facies (cobbly limestone) and a southeastern facies (black limestone and graptolite shale). A section near Lantz Mills consists mainly of limestone, and a corresponding section of graptolite shale and limestone is cited near Front Royal. On their map these two sections lie about 20 miles apart. However, assuming that the original isoliths are now trending about northeast-southwest and projecting the positions of these sections, the distance perpendicular to the original isoliths from cobbly limestone section to black shale and limestone section is reduced to 14 miles.

While mapping in the intervening area is incomplete, at present there seems to be no objection to projecting this same change of facies along the Appalachian valley and into New York. The writer knows of no occurrence of well-developed Bolarian limestone so close to known Normanskill beds as to make such a facies change improbable. The same statement can be made for the Chazyan limestones and the Deepkill beds.

Attention should be drawn again to the limestone beds found in the Normanskill along the western margin of the Kinderhook quadrangle. Ruedemann (1942a, p. 90) also mentions calcareous zones in the Normanskill in the Catskill quadrangle. At the type section the Deepkill shale contains many limestones, some of which are described as 6, 14, and 16 feet thick (Ruedemann, 1902, p. 546–549). Cooper and Cooper (1946, p. 61) have drawn attention to the occurrence of upper Normanskill graptolites in pebbles of Chambersburg age in the Rysedorph conglomerate (Ruedemann,

1930, p. 106–107); thus it seems probable that the limestone and shale facies in New York also were gradational and not formed in separate depositional basins.

The writer therefore concludes that there is at present no reason for considering the distribution of Bolarian and Chazyan rocks incompatible with an interpretation involving normal facies changes. The demonstrated relations in Virginia virtually remove the necessity for overthrusting of any magnitude to explain the known conditions in eastern New York and New England.

Canadian—Within the Kinderhook quadrangle the only known rocks of Canadian age are those in the string of outcrops along the Chatham thrust. Throughout the region around the quadrangle are similar Canadian carbonate rocks. All but the highest units of these rocks are dolomitic and tend to contain quartz sand. The entire area seems to have been a shallow, unstable shelf during the Canadian. These sediments are remarkably uniform over the area, and lithologic units can be traced a considerable number of miles along the strike.

To the south, Canadian beds have been described by Weaver (1953, Ph.D. thesis, Univ. of London) in the Copake quadrangle, Knopf (1927, p. 438–9) in the Millbrook quadrangle, Gordon (1911, p. 48–82) in the Poughkeepsie quadrangle, and Holzwasser (1926, p. 35–43) in the Newburgh quadrangle. Lewis and Kummel (1940, p. 71–73) cite Canadian beds in the Kittatinny limestone of New Jersey.

Canadian carbonate rocks are well developed in the Mohawk valley (Fisher and Hanson, 1951; Fisher, 1954) and northward in the Champlain valley (Brainerd and Seely, 1890; Kemp and Ruedemann, 1910, p. 65–68; Rodgers, 1937, p. 1576–1579, 1952, p. 35) and in west-central Vermont (Cady, 1945, p. 539–548). Prindle and Knopf (1932, p. 273–4) and Bonham (1950, Ph.D. thesis, Univ. of Chicago) have described Canadian carbonate rocks from the Taconic quadrangle.

One major stratigraphic problem of the region is the relationship of these Canadian limestones and dolomites to the Deepkill shale sequence. If the Deepkill shale represents only the uppermost Canadian, then it might originally have been deposited as part of the normal sequence following the middle Canadian in the region where it is now found. The subdivisions of the Canadian carbonate rocks of the Lake Champlain area have not been traced systematically southward, and such names as "Wappinger limestone" have not generally been subdivided, with the exception of the careful work of E. B. Knopf (1927) and John Weaver (1957). Consequently, attempts at evaluating the possibility of the Deepkill overlying these beds must be for the present speculative. However, D. W. Fisher (Personal communication) has noted the apparent absence of the upper Canadian from near Copake northward to Washington County—approximately the belt in which the Deepkill is known to occur. Thus it is not at all improbable that the Deepkill may represent some part of the upper Canadian and the Chazyan, as suggested previously.

As these tentative correlations seem to be forcing the argument against the "klippe" hypothesis, the distribution of these carbonate rocks should be carefully scrutinized. Known Canadian outcrops show that the "Taconic klippe" is practically surrounded by these carbonate rocks which in Vermont seem to become argillaceous toward the east. According to the "klippe" hypothesis, Canadian rocks should be represented within the "klippe" as argillites in contrast to the surrounding carbonate rocks. But apart from the Deepkill beds, which are here interpreted as mainly Chazyan, no argillites of Canadian age are known in the "klippe", except possibly the local Schaghticoke beds.

In the Kinderhook quadrangle, instead of argillites, remnants of the carbonate sequence lie on Lower Cambrian slates. They contain the *Lecanospira* fauna and are lithologically identical with the corresponding beds in the typical carbonate sequence. These beds seem to rest on Lower Cambrian slates; they do not appear to "stick up through" an allochthonous argillite sequence. Furthermore, if their interpretation as slivers along a thrust is correct, it is also more probable that they originally rested upon the older slates which were later thrust over them.

If these Canadian carbonate rock remnants

rest upon the slate sequence, then they need not have been carried any distance by thrusting—as they would have to be were they resting upon an allochthonous sequence. Indeed, their similarity to acknowledged autochthonous beds in the region and suspected tendency of the Canadian to become argillaceous to the east constitute strong reasons for doubting if these beds could possibly have been displaced any great distance.

If the preceding arguments are corroborated by future detailed studies, the stratigraphy of the Ordovician rocks can be explained without the klippe hypothesis. The evidence for its existence must then be sought in the distribution and correlation of the Cambrian formations.

Upper Cambrian.—The Upper Cambrian carbonate rocks are distributed about as those of the Canadian and with them constitute the "autochthonous" facies. Sandstones and dolomites are the prevalent lithologic types, and *Cryptozoon* reefs are common throughout the region. The seas transgressed a Middle Cambrian lowland during the Late Cambrian, and shallow-shelf conditions apparently prevailed in this region through most of Late Cambrian and Canadian time.

Weaver (1957) assigned certain argillites in the Copake quadrangle to the Upper Cambrian, explaining them in the same way as the supposed Canadian argillites—*i.e.*, by normal facies change within an indigenous sequence. Other than in the Copake quadrangle Upper Cambrian argillites have not been reported within the "klippe" and so are not significant in this discussion.

Middle Cambrian.—Near St. Albans in northwest Vermont 300 feet of Middle Cambrian conglomerate and slate is locally exposed (Schuchert, 1937, p. 1039–1044). Southward along the Cambro-Ordovician belt the Middle Cambrian is next exposed as a limestone unit in Pennsylvania.

The Hudson valley region evidently was gently arched into a broad lowland during the Middle Cambrian. Evidences of folding during this interval are lacking. Wherever described, contacts between the Lower and Upper Cambrian strata are essentially conformable.

Lower Cambrian.—Wheeler (1947) has recommended placing the base of the Lower Cambrian at the base of the *Olenellus* biozone; Resser and Howell (1938) also draw the base at the bottom of the lowest fossiliferous formations in the Appalachians. While this classification is most satisfactory for long-distance correlation, in this discussion the local usage of the term "Lower Cambrian" must be considered. Recent authors (Thompson, 1952; Osberg, 1952; Brace, 1953) have included the Mendon Series, which apparently underlies fossiliferous Cheshire quartzite, in the Lower Cambrian. To date no fossils have been found in the Mendon, but there is evidently some doubt as to its relationship to fossiliferous Lower Cambrian rocks (Thompson, 1952, p. 16). Because of this uncertainty and for clarity in regional analysis, the writer also includes the Mendon Series and its equivalents in the Lower Cambrian without entering into the problem of their ultimate correlation.

In most cases, correlations in the Lower Cambrian of this region cannot be considered established with the desirable precision. However, an approximate paleontologic marker zone can be established throughout the region—*i.e.*, the level of the lowest occurrence of Cambrian fossils. According to Resser and Howell (1938), Knopf (1927, p. 433-437), and Fowler (1950, Pl. I), the following formations seem to be about time equivalent: the Gilman quartzite of northern Vermont, the Cheshire quartzite of southern Vermont and Massachusetts, the Bomoseen grit of the "Taconic sequence", the Poughquag quartzite of southeastern New York, the Hardyston quartzite of New Jersey, and the Antietam quartzite of the southern Appalachians. Analysis of the Lower Cambrian in this region can best be studied by relating the units to this one zone or group of closely associated zones, with the understanding that the resulting correlations are only approximate.

Booth (1950, p. 1136) describes pre-Gilman rocks 500–1000 feet thick in the Oak Hill slice of northern Vermont. To the south, Osberg (1952, p. 21) assigns a thickness of 800–1800 feet to the Mendon Series (pre-Cheshire), and Brace (1953, p. 29) describes the same rocks as 525–1750 feet thick near Rutland. Immediately south of Rutland no

information is available but 35 miles to the south, in the Taconic quadrangle, the Mendon Series is either missing (Prindle and Knopf, 1932), or thinned and mapped as lower Cheshire (John Rodgers, personal communication) and rests on the Precambrian.

In the quadrangle west of Rutland, Fowler (1950) described two sequences which he indicates as time equivalent on his correlation table. The Mendon Series, part of the "autochthonous" sequence, is assigned a minimum thickness of 2000 feet; the pre-Bomoseen formations (Nassau and Bird Mountain), part of the "allochthonous" sequence, are described as 1000–2500 feet thick.

The Mendon Series, as described by these authors, is essentially a heterogeneous complex of conglomerate, graywacke, argillite, and occasional carbonate rocks. However, the same description is almost as accurate for the Rensselaer-Bird Mountain-Nassau beds in the "allochthonous" sequence. While direct correlations between these two sequences are not now possible, there can be little doubt of the overall similarity of these "allochthonous" and "autochthonous" sequences. This lithologic similarity, their identical stratigraphic positions, the apparently rapid disappearance or thinning of the Mendon Series south of Rutland, and the continuity in trend of these two sequences suggest that they are probably both indigenous rocks, possibly deposited in a long linear trough, These rocks continue southward through the Rensselaer plateau (Dale, 1893; Balk, 1953) and the Kinderhook quadrangle and apparently vanish in the southern Copake quadrangle where they are probably represented in the grits that Weaver (1957) interprets as protruding upward through the Trentonian slate.

The rocks above the Mendon and its equivalents can be best described in two groups. In west-central Vermont and southward along the west flank of the Green Mountains, the post-Mendon Lower Cambrian is composed of a basal conglomerate or quartzite overlain by a carbonate sequence; these beds are several thousand feet thick in Vermont but thin southward into New York and New Jersey. West of these quartzites and carbonate rocks a belt of argillite and interbedded quartzite and carbonate rock extends from near the north end of the Taconic Range southward into the Hudson River valley.

That the Mendon series and the Rensselaer graywacke were derived mainly from western sources has been suggested by Booth (1950, p. 1156–1157) and Balk (1953, p. 824–827), respectively. However, it does not follow that all the Lower Cambrian must have had a similar derivation. Indeed, angular unconformity between the Mendon below and the Cheshire above is reported as far north as Lake Dunmore, Vermont. Southward the Cheshire has transgressed upon an erosion surface of old Precambrian. The conclusion that there was a land of some type along the present western edge of the Green Mountain-Hudson Highland axis before deposition of the Cheshire and Poughquag seems unavoidable; the critical question concerns the area just to the west—was it a lowland, or a depositional basin in which the Lower Cambrian sequence of the Hudson valley was originally laid down?

The two belts of post-Mendon Lower Cambrian rocks are at least several miles apart. The closest occurrence seems to be in the Taconic quadrangle (Prindle and Knopf, 1932, p. 268–269), but Bonham (1950, Ph.D. thesis, Univ. of Chicago) found that some of these outcrops of "Rutland dolomite" are not Lower Cambrian, as assumed by the original authors, but are Canadian. Knopf (1946) reports "Lower Cambrian" phyllites overlying apparently synchronous Lower Cambrian quartzite and dolomite; the results of Weaver (1957) and the writer suggest that the phyllites are rather of Trentonian and Deepkill ages. Lower Cambrian fossils in the predominantly argillitic beds apparently have not been reported south of the Schodack Landing locality in the Coxsackie quadrangle (Goldring, 1943, p. 81–84); accordingly there is doubt about the southern limit of the true Lower Cambrian as opposed to its "double" in the Deepkill.

It therefore seems possible to interpret these two post-Mendon Lower Cambrian sequences as facies deposited essentially where they rest today. The writer knows of no evidence for unconformity, structural or stratigraphic, between the Bomoseen and the underlying rocks. Therefore, if the Bomoseen and higher

beds were thrust a great distance, then the Rensselaer graywacke and Nassau beds must have come with them. However, the relationship between these beds and the Mendon Series is such that large displacements of one sequence relative to the other is rather improbable.

This interpretation has been supported previously in the literature. Pumpelly *et al.* (1894, p. 26–28) postulated an eastern source for the Cheshire on the basis of petrologic comparison to Precambrian rocks in the Green Mountains. Inspection of Balk's (1936) map and the work of Agar (1932) suggest that the Poughquag quartzite may thin and disappear to the east. Keith (1932, p. 393–394) was concerned over the southward disappearance of the Mendon and considered the pre-Cheshire unconformity important. In reconstructing the history of the Connecticut valley Bain (1932, Fig. 8) showed a lowland along the Green Mountain axis during Early Cambrian time. Fowler (1950, p. 16) discussed the problem of pre-Cheshire folding and suggested that it might increase to the south.

Of particular interest, however, is the section on the Lower Cambrian in a paper by Swartz (1948, p. 1527–1534, Figs. 12, 13). Inspection of his isopachous map reveals that very little is known about the Lower Cambrian west of the Hudson valley from the latitude of the Adirondacks southward to central Pennsylvania. His reconstruction of the paleogeography shows a lowland along both sides of the trough and the Taconic sands and clays being deposited adjacent to the eastern borderland. The writer suggests as another alternative the following slight revision of this interpretation:

A land must have been present along the western margin of the basin in the latitude of northern Vermont during Early Cambrian time to account for the clastic rocks there. However, no information on the Lower Cambrian west of the Hudson valley is available, and the Adirondack lowland might well have been limited to the north while the majority of eastern New York was covered with a shallow sea. The presence of a lowland during part of Early Cambrian time along the eastern margin of the trough, suggested by the fact that the Cheshire and the Poughquag rest unconformably upon the Precambrian gneisses, would account for the marginal sands and carbonates and offshore argillites, just as the present-day facies are arranged.

Summary.—The foregoing interpretation of the regional stratigraphy removes the necessity for, if not the possibility of, the existence of the "Taconic klippe;" it also involves inferences yet to be tested conclusively in the field. Until certain key areas are mapped in detail, it will be impossible definitely to resolve the dispute. However, the writer feels that within the limits of our understanding to date the interpretation presented here involves fewer difficulties than one calling for a far-travelled klippe.

Cambro-Ordovician History

The oldest known rock in the quadrangle is the Rensselaer graywacke. Balk (1953, Pl. 4) has shown that the coarsest phases of this rock are found to the west, and it was probably derived in the main from an ancient highland forming the edge of the Early Cambrian continent. Rocks of this age today form a linear belt extending northward to the international boundary and southward for a lesser but undetermined distance. They are not found in the lower Hudson valley, but equivalent rocks reappear in Pennsylvania and in the southern Appalachians. The Rensselaer-Mendon rocks are not found west of their main belt of outcrop, and their extent to the east is obscure; recent work in Vermont (Osberg, 1952; Thompson, 1952; Brace, 1953) suggests that these early Cambrian sediments may have extended eastward a considerable distance.

The Rensselaer graywacke is overlain by a series of quartzites that are finer-grained than the Rensselaer; this general upward decrease in grain size probably reflects the wearing down of the western source of clastics. Shortly after this ancient highland had been reduced and argillaceous muds were being deposited in the basin, a new uplift formed a lowland several miles to the east. Along the western shore of this new landmass the relatively pure Cheshire and Poughquag sands accumulated, while the finer materials were winnowed out and de-

posited to the west as the Bomoseen-Schodack sequence. As the lowland diminished, the earlier clastics gave way to chemical deposition, and a thick series of sandy dolomites and limestones was formed near the shore; offshore a thinner sequence of limestone and shale was deposited.

During the Middle Cambrian a gentle warping elevated the entire area from northern Vermont to Pennsylvania, and the Lower Cambrian strata must have been greatly reduced in the ensuing interval of erosion, especially toward the west.

In the Late Cambrian the area gently subsided, and the transgressing seas slowly covered the old erosion surface. The abundance of oölites, *Cryptozoon* reefs, and sandy carbonate rocks suggests regional shelf conditions, which apparently prevailed through most of the Canadian epoch as well. Unconformities are common in the Upper Cambrian and Canadian strata of the region, and these rocks must have been deposited in times of shifting seas and general instability.

In the Kinderhook quadrangle middle Canadian carbonate rocks rest on presumed Lower Cambrian slates; a few miles to the southeast, however, equivalent Canadian strata are underlain by lower Canadian and Upper Cambrian carbonate rocks. It is therefore inferred that the eastern slate, quartzite, and graywacke terrane of the Kinderhook quadrangle stood as a low island (or peninsula) in the encircling Late Cambrian seas.[4] During the Canadian, the seas gradually inundated this lowland; the middle Canadian seas covered the area with a thin carbonate deposit.

Late in the Canadian the sea withdrew, and erosion removed some of the Canadian strata. A gentle subsidence of the region resulted in a new transgression of the seas, and these new conditions persisted through most of the Chazyan and Bolarian. To the northwest the upper Canadian, Chazy, and Black River limestones were deposited on the shallow shelf while the Deepkill and Normanskill shales accumulated in the deeper basin to the southeast. The conglomerates of the Deepkill contain many rounded limestone pebbles and reflect the transgression of the seas upon a limestone terrane.

Ruedemann and Wilson (1936, p. 1557–1563) have maintained that the radiolarian content of the Deepkill and Normanskill cherts necessitates a depth of water of at least 12,000 feet in this trough during their deposition. Other writers (Taliaferro, 1934, p. 208–209; Chadwick, 1946, p. 586; Kuenen, 1950, p. 359), however, have denied that radiolarian cherts necessarily imply such abyssal depths.

Ordovician volcanic rocks are present to the east (Kay, 1951, p. 53), and volcanic islands were probably the source of the fine clastics in this argillitic sequence. This volcanic activity very likely provided the silica for the abundant chert deposits in these beds.

Late in the Bolarian the fine argillites and cherts of the Mount Merino beds were replaced by the coarser graywackes of the Austin Glen. These coarser clastics must have been shed by a rising landmass, believed to be the result of moderate regional warping and uplift in the east. This steady emergence continued, and by the early Trentonian a lowland was present through most of western New England and eastern New York

Vigorous erosion beveled this land, exposing rocks as old as Precambrian, before it was covered by the early Trentonian seas. Thin limestone deposits accumulated in these shallow seas, but the presence of low islands probably prevented uniform deposition over the entire area. Early Trentonian shore lines apparently were unstable, for local unconformities are found within and above these limestones; limestone conglomerates are developed in some places.

In middle Trentonian time the Vermontian disturbance (Kay, 1937, p. 290) produced uplift to the east and buried the entire region beneath a blanket of black mud and silt. This Trentonian slate is the youngest Ordovician rock

[4] Weaver (1953, Ph.D. thesis, Univ. of London) visualized a different Upper Cambrian and Canadian paleogeography. He correlated the slate and quartzite sequence with the Upper Cambrian and Canadian carbonate rocks in the eastern part of the Copake quadrangle and interpreted these shales and sands as a lagoonal facies of their eastern equivalents. According to this interpretation the area pictured here as a Late Cambrian island would become instead a shallow basin. The present writer's reasons for opposing this interpretation have been stated previously, but the possibility of its correctness cannot be dismissed.

now preserved in the Kinderhook quadrangle.

Later deformation, presumably related to the Taconian disturbance, caused the intense folding of the Cambro-Ordovician strata—as observed below the unconformity at Mount Ida. Most of the thrusting in the region probably also developed at this time, but how much of the deformation of these rocks was accomplished by the later Acadian and Appalachian disturbances cannot be determined in the Kinderhook quadrangle.

Conclusions

Geologic mapping in the Kinderhook quadrangle and a survey of the literature show that there are good reasons for rejecting the hypothesis of the "Taconic klippe."

Structural evidence is scarce, but data available weigh against the acceptance of this hypothesis. The most serious problem is the difficulty in satisfactorily defining the boundaries of the " Taconic klippe."

Nor does analysis of the regional stratigraphy reveal any necessity for the presence of a "klippe"; an interpretation is possible which removes the seeming anomalies that originally fostered the klippe hypothesis. This interpretation involves certain assumptions which are probable but are not established. The most critical of these is the assignment of a late Canadian and Chazyan age to the Deepkill beds; the validity of this correlation must be tested by further detailed work in the lower Hudson valley. Another basic but controversial assumption is the revised interpretation of Lower Cambrian paleogeography.

Geologists' final verdict on the "Taconic klippe" may not be rendered for many years; but at present the klippe hypothesis seems to lack positive supporting evidence and to be unnecessary in explaining the known geologic relations.

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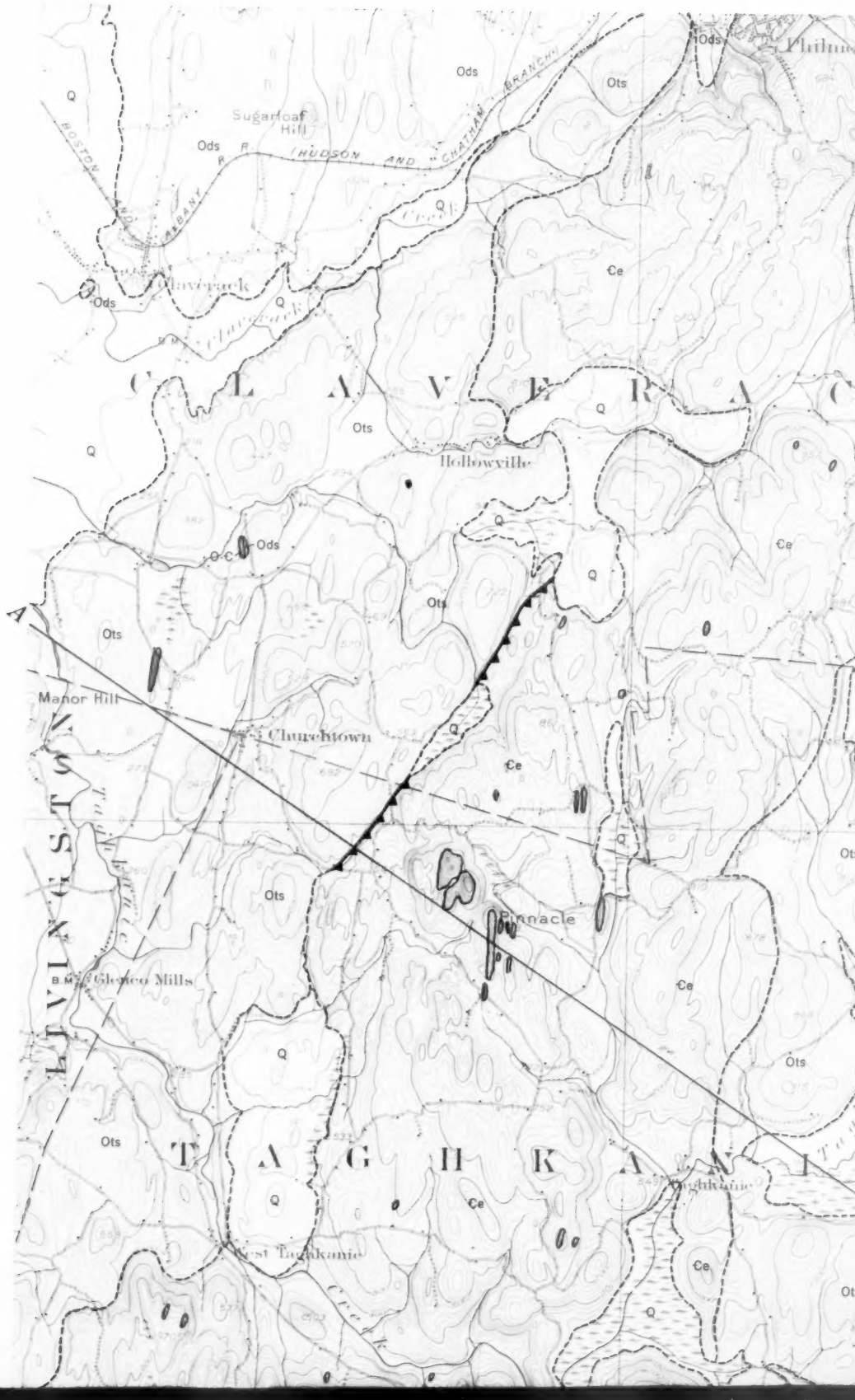
Manuscript Received by the Secretary of the Society, May 20, 1954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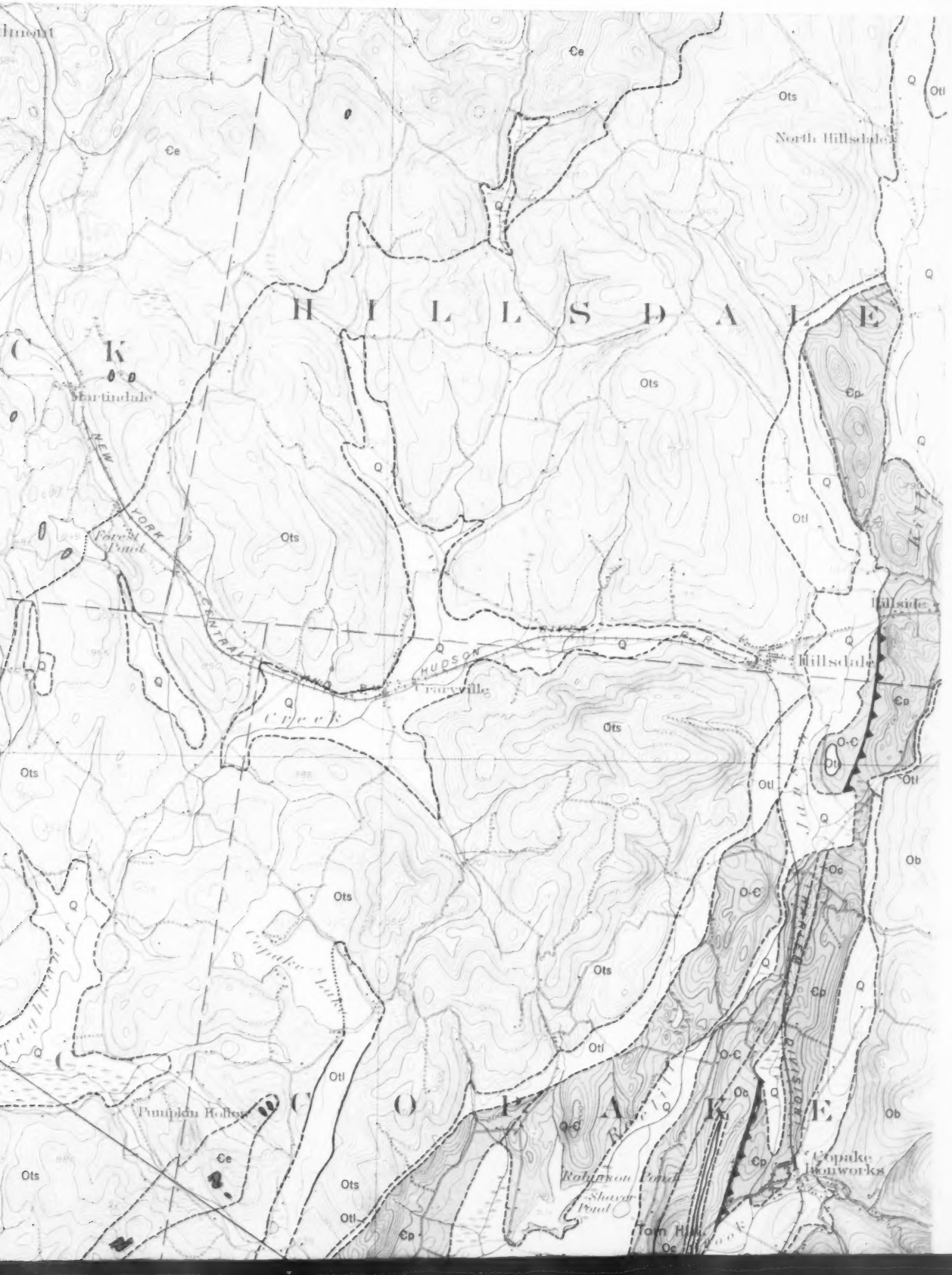

North Hillsdale
HILLSDALE
Hillsdale
Martindale
Forest Pond
NEW YORK CENTRAL RAILROAD
HUDSON RIVER R.R.
Copake
Pumpkin Hollow
Robinson Pond
Sharon Pond
Copake Ironworks
Tom Hill
Ots
Otl
Ob
Oc
O-C
Cp
Ce
Q

North Hillsdale
HILLSDALE
Hartindale
Forest Pond
Hillsdale
Claryville
Creek
Copake Lake
Pumpkin Hollow
COPAKE
Copake Ironworks
Robinson Pond
Shaw Pond
Ots
Otl
Co

Weaver, Pl. 1

EXPLANATION

Q

Superficial deposits

Glacial deposits and alluvium; boulder clay, gravel, and sand, lake clays, etc. Distinguished only where they seriously obscure bedrock

QUATERNARY

UNCONFORMITY

Ots Otl

Trenton black slate, Ots; with basal limestone, Otl

Trentonian

Ob

Berkshire schist

Quartz-chlorite schist, with basal limestone. Grades westward into the Trenton slate

UNCONFORMITY

Chiefly Canadian

Ods

Deepkill shale

Oc

Copake limestone

Dolomitic limestone, with basal sandstone

O-C

Undifferentiated Cambro-Ordovician dolomites

ORDOVICIAN

Cp

Pine Plains formation

Dolomites, quartzites, and shales

UPPER CAMBRIAN

Ce

Elizaville shale

Gray to greenish shale

MAINLY CAMBRIAN (POSSIBLY INCLUDING SOME LOWER ORDOVICIAN)

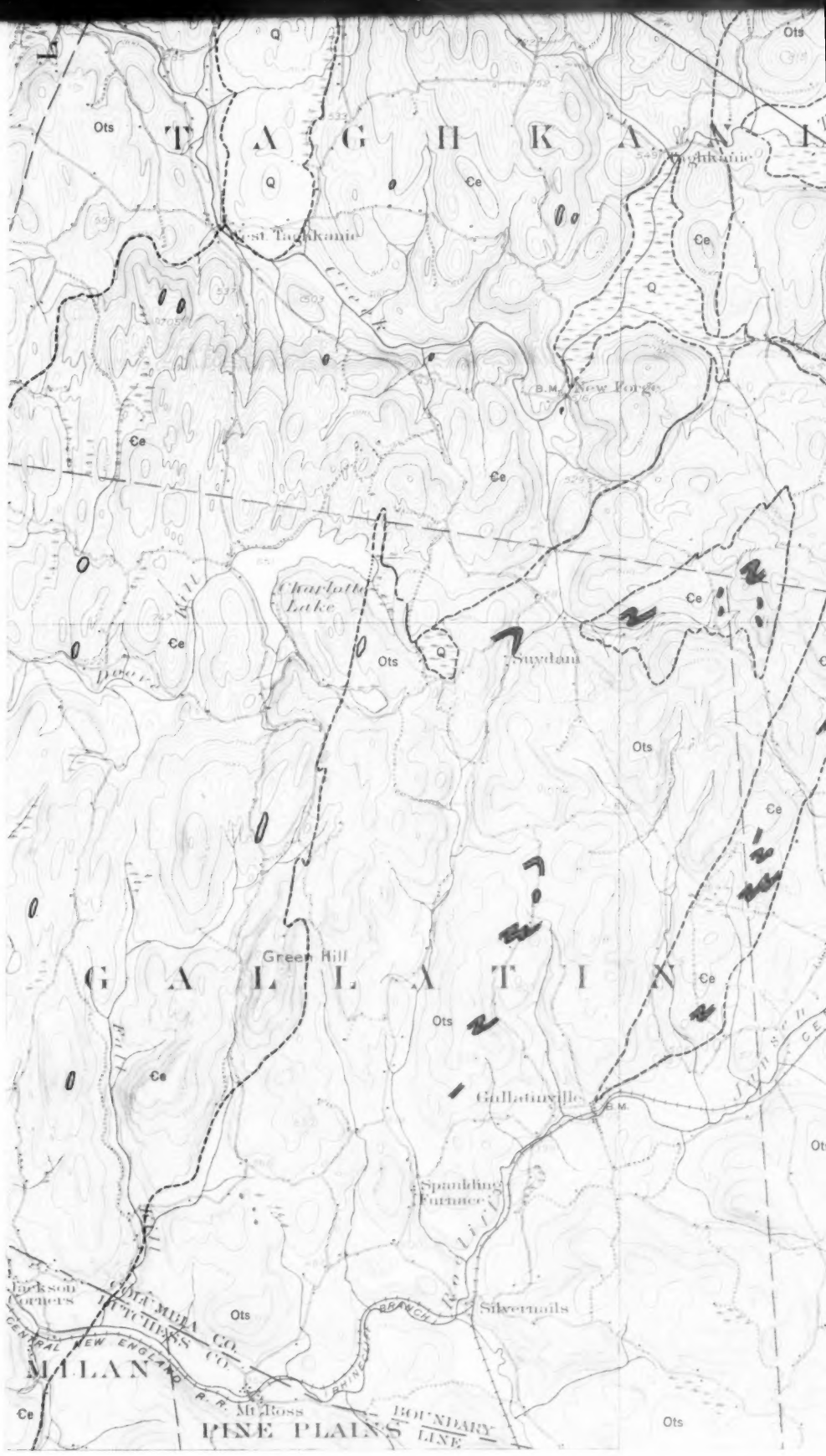
Calcareous grit layers in Elizaville shale

Some appear in Trenton shale area along local anticlines

Gray-green quartzite in Elizaville shale

Contact, dashed where inferred

Because of intense crinkling and folding of all slaty formations and lack of continuous exposures, the location of such contacts is approximate at best



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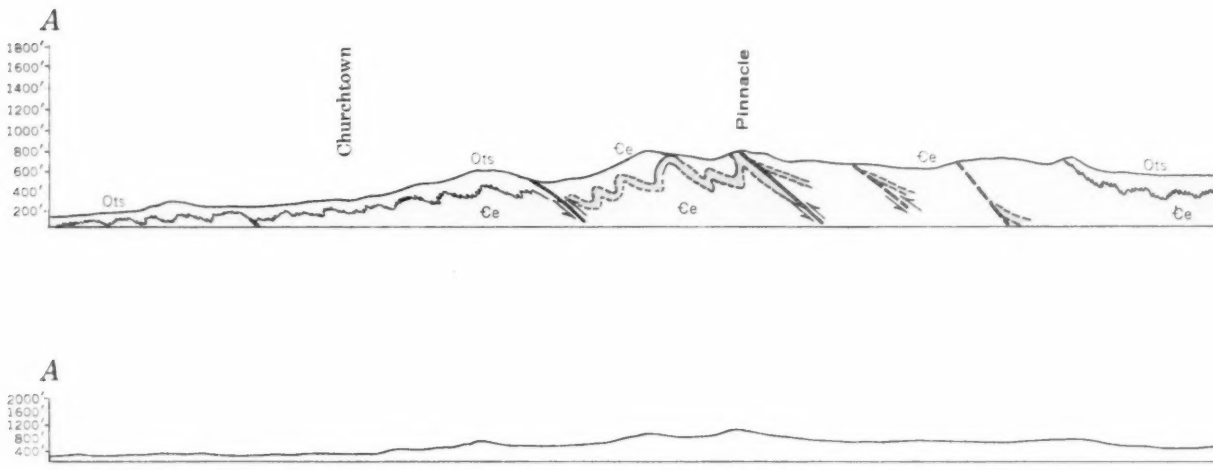

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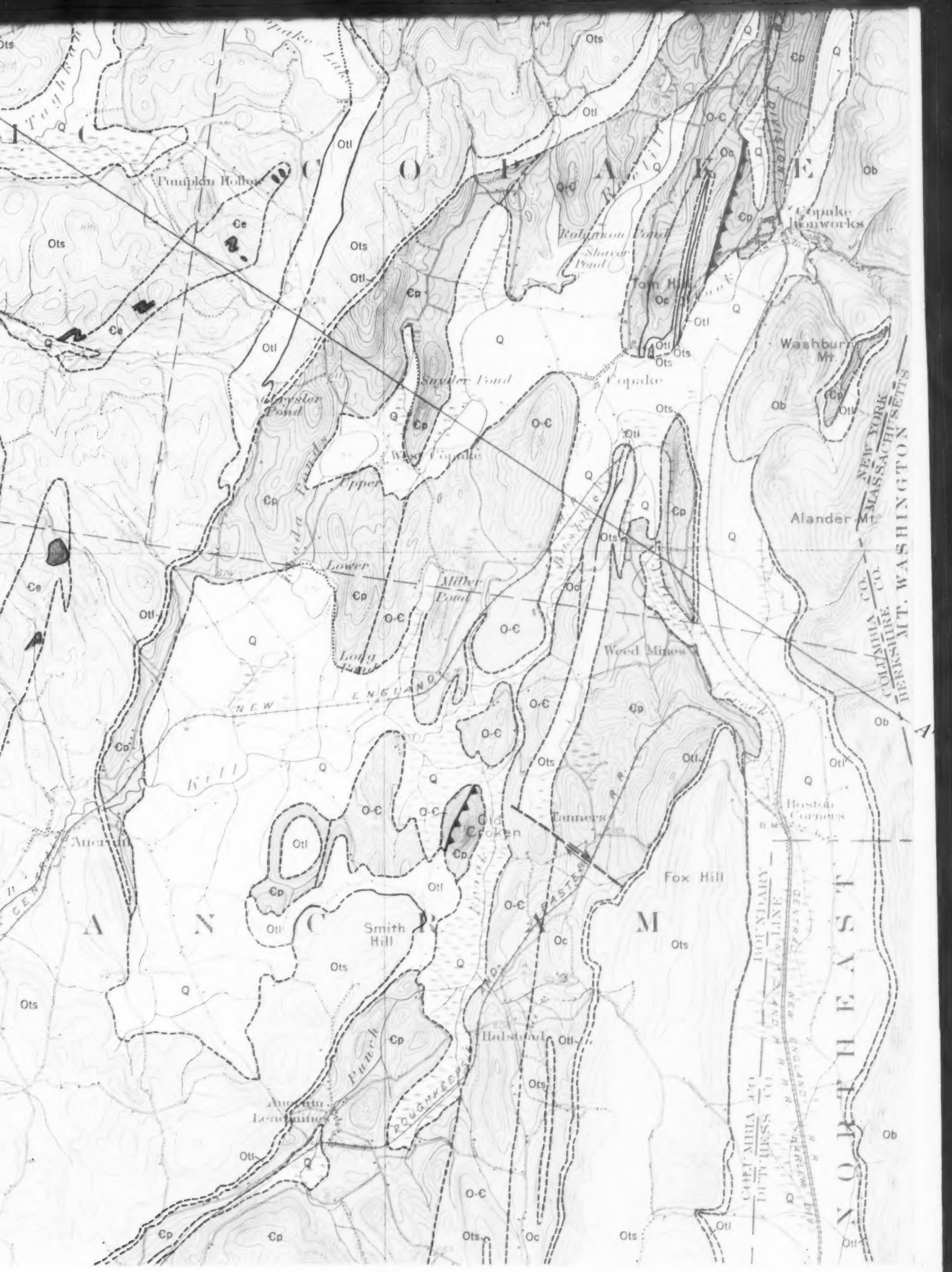

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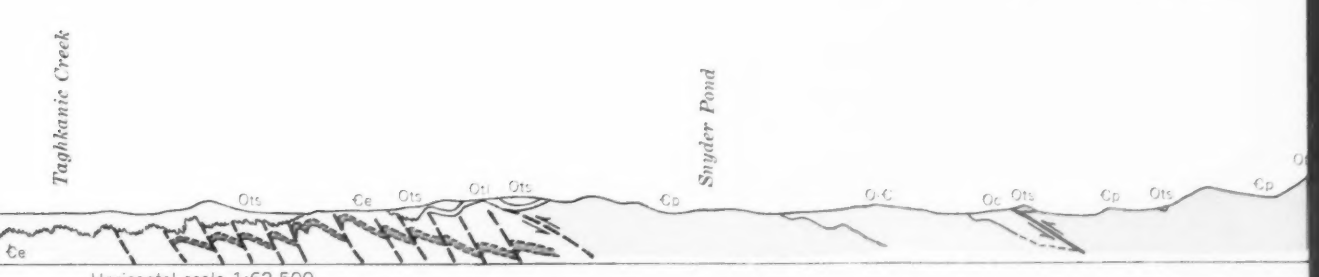

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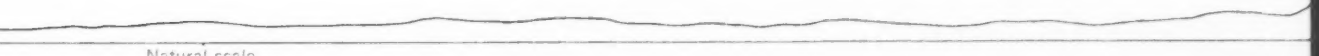


Natural scale

SECTIONS OF THE COPAKE QUADRANGLE, NEW YORK

Scale $\frac{1}{62500}$

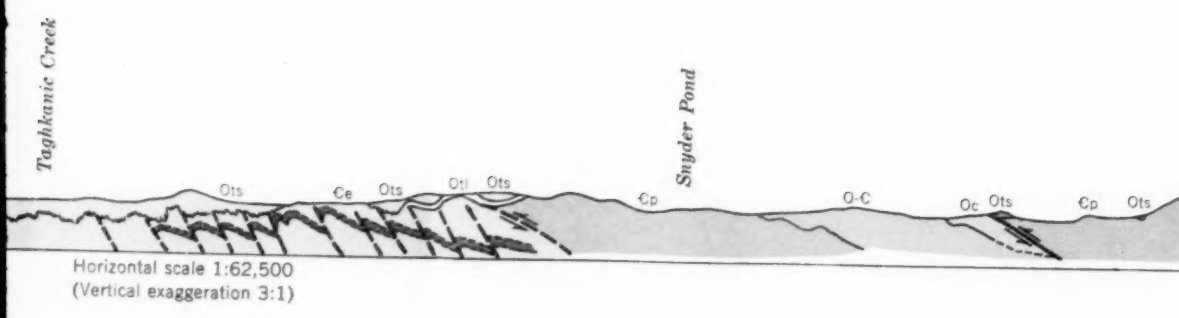
1 2 3 4 Miles

1 2 3 4 5 Kilometers

Contour interval 20 feet

Datum is mean sea level

Geology by J. D. Weaver, 195



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Scale $\frac{1}{62500}$

1 2 3 4 Miles

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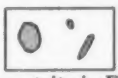
Calcareous grit layers in Elizaville shale

Some appear in Trenton shale area along local anticlines



Gray-green quartzite in Elizaville shale

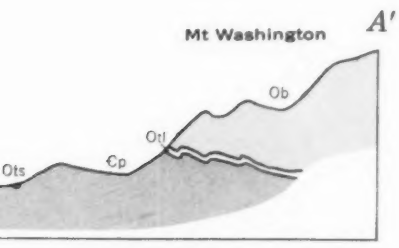
Contact, dashed where inferred

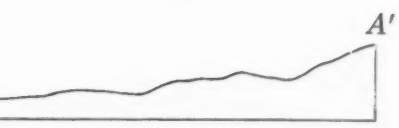
Because of intense crinkling and folding of all slaty formations and lack of continuous exposures, the location of such contacts is approximate at best

Thrust fault

Inferred tear fault

, 1950-52





BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 68, PP. 725-762, 8 FIGS., 4 PLS. JUNE 1957

STRATIGRAPHY AND STRUCTURE OF THE COPAKE QUADRANGLE, NEW YORK

BY JOHN DODSWORTH WEAVER

ABSTRACT

The area of the Copake, New York, quadrangle lies centrally in what has been described formerly as a klippe of a large overthrust sheet of Cambro-Ordovician argillaceous rocks, thrust westward about 40 miles over carbonate rocks of similar age. The argillaceous rocks are divisible into an older (Late Cambrian to Early Ordovician) group, here named the Elizaville shales, and a younger group of Trentonian shales lying unconformably above the Elizaville shales and the Cambro-Ordovician carbonate rocks. A thin limestone at the base of the Trenton shales wedges out westward.

The structure is imbricate. Most faulting was pre-Trenton; further movement involving the Trenton rocks has occurred mainly along faults in the underlying rocks. No evidence supports the klippe hypothesis, and the facies changes which engendered it can be explained as associated with offshore reef-girt islets or perhaps back-reef conditions.

The Berkshire schist in the eastern edge of the quadrangle is the metamorphosed equivalent of the Trentonian shales.

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INTRODUCTION

Geologic mapping of the Copake quadrangle on the eastern border of the State of New York (Fig. 1) has enabled investigation of the "Taconic thrust" hypothesis, upon which the appropriate part of the Tectonic Map of the United States is based (King *et al.*, 1944). According to this hypothesis the Hudson River slates, which predominate in the Copake quad-

rangle, are part of a large klippe which has been thrust westward as much as 40 miles over the autochthonous series mainly of carbonate rocks. Such a thrust would constitute a major structural element in the United States.

However, evidence of the intense deformation that would accompany such a great translocation, particularly of argillaceous rocks, is scarce, and no eastern edge of the klippe or root zone to the east has been recognized.

Clarification of the structure in this area would facilitate study of the more highly metamorphosed rocks to the east. Once this foundation is laid, the Taconic area would be an extremely fruitful one in which to study the processes of regional metamorphism. The structure and stratigraphy of these metamorphic rocks will also help indicate the age of the crystalline rocks of the Manhattan Prong and of the New Jersey Highlands.

Acknowledgments

The writer wishes to thank particularly Professor Walter H. Bucher who introduced him to the problem, has been a continual source of inspiration, constant critic, and frequent companion and friend in the field. Gratitude is also expressed to the New York State Science Service and its Director, Dr. Carl E. Guthe, and to the Council of the Lamont Geological Observatory of Columbia University for financial assistance.

Dr. Winifred Goldring (former State Paleontologist, New York), Dr. Rousseau Flower, Dr. Marshall Kay, Dr. E. B. Knopf and Dr. S. Warthin, Jr., have accompanied the writer in the field and contributed most helpful discussion. Dr. G. A. Cooper, the late Josiah Bridge, Dr. Marshall Kay, and Dr. H. B. Whittington have kindly examined and commented on the fossils. To all these grateful appreciation is recorded.

Finally the writer adds a word of thanks to his friends and colleagues both on the Faculty and among the students at Columbia University whose interest and interchange of ideas were of constant value.

History of Research

The Copake, New York, quadrangle is situated in the middle of the large area shown on the Tectonic Map of the United States as a klippe of Cambro-Ordovician argillaceous rocks; these are represented as resting on carbonate rocks of the same general age which show through in windows or fensters; one large fenster occurs partly in the Copake quadrangle.

The western edge of the Berkshire Mountains enters the quadrangle in the east. Emmons (1842) founded his Taconic system on the rocks of the Taconic Range which includes the Berkshires. His theory caused much controversy until 1888, when Walcott proved it untenable (Dana, 1882; 1885; 1887). The main question was whether the schists of the Taconic Range lay conformably above the limestones and were thus younger and therefore metamorphosed equivalents of the Hudson River shales which extend north-south, west of the carbonate belt, or whether they were older than the carbonates and the sequence was inverted by folding. Dana (1882) adduced strong arguments favoring the former interpretation; he described the Taconic Range as a simple syncline.

Fossil evidence indicated that the carbonate sequence ranges from Cambrian to middle Ordovician (Walcott, 1888; Dwight, 1879–1889), and the shales and schists would thus be later Ordovician. Dale (1899; 1904) did extensive work in the region, particularly on the shale sequence.

In 1913, Keith's work in the northern part of the Taconic Range suggested that the structure was not so simple as had been thought, since he found Cambrian rocks there involved in imbricate thrust structures. Ruedemann meanwhile had been doing more detailed paleontological work in the Hudson River shale terrane and had found there, too, lower Cambrian rocks in places clearly overthrust on Ordovician rocks. In the Saratoga-Schuylerville quadrangles he interpreted the structure as many small thrust slices that give rise to an imbricate or "Schuppenstruktur" with considerable over-all displacement. His map was the first to show this thrusting. It displays four major lines of faulting, though the text refers to "innumerable slip planes or small thrust faults" (Cushing and Ruedemann, 1914, p. 103).

In 1927 E. B. Knopf made a brief reconnaissance of the southern Taconic area and suggested that the schists of the Taconic Range

had been overthrust from the east and were Precambrian.

By 1932 Prindle and Knopf, working in the transportation "of at least 40 miles and possibly as much as 70 miles".

A palinspastic map of the eastern United

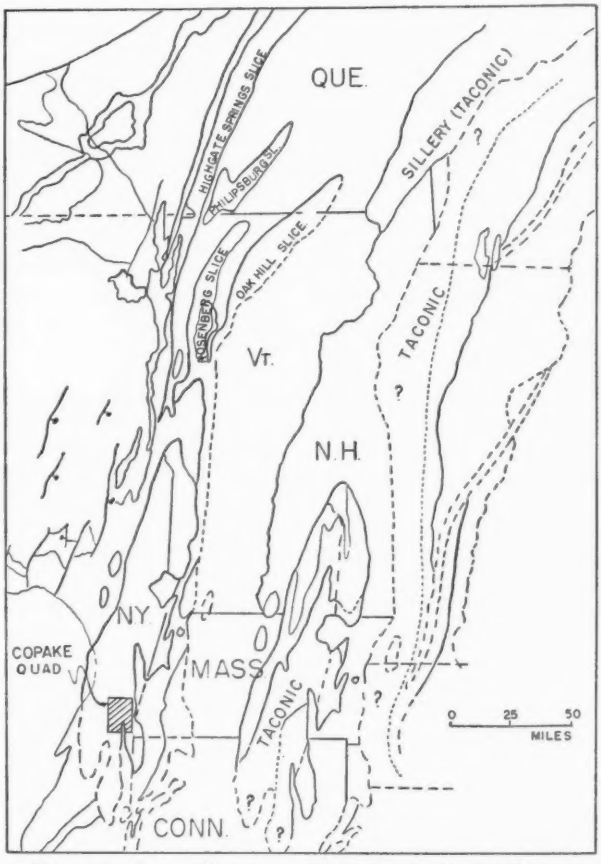

FIGURE 1.—SKETCH MAP OF THE NORTHEASTERN UNITED STATES
Showing the Taconic allochthone and its inferred original position (after Kay, 1939).

"Taconic quadrangle" (an area straddling the southwest corner of Vermont, the northwest corner of Massachusetts, and the neighboring parts of eastern New York) concluded that the slates were thrust over the carbonates; that the argillaceous rocks had been carried from a separate depositional environment east of the Green Mountain axis—a distance of at least 40 miles (Prindle and Knopf, 1932, p. 297). In the same year Keith expressed similar views in describing the geology of northwest Vermont. Schuchert (1937, p. 1028) proposed westward

States (Kay, 1937, Pl. 5) shows these thrust sheets in their inferred original positions and shows the klippe or Taconic allochthone as including both the schists of the Taconic Range and the shales of the Hudson River terrane (see Fig. 1). Kay (1942, p. 1618) accepts the overthrust concept without discussion beyond suggesting that the facies contrasts support this interpretation.

Ruedemann's map of the Capital district and Goldring's of the Coxsackie quadrangle show the whole shale sequence as overthrust west-

ward; the western line of overthrust passes under the Helderberg escarpment of Silurian rocks southwest of Albany. The imbricate nature of the structure is, however, emphasized in the supporting text (Ruedemann, 1930, p. 137; Goldring, 1943, p. 281).

Later workers in Vermont (Cady, 1945; Fowler, 1950) have mapped the line of overthrust; Flower (1949) and Rodgers (1952) have also adopted the klippe hypothesis. Large-scale thrusting is present, but no evidence shows it to be of the nature suggested by Prindle and Knopf. Search for evidence of roots for such a thrust on the east side of the Green Mountains has been unsuccessful (Hawkes, 1941). The relationship is, then, merely inferred. Much of the klippe area has not yet been mapped in detail.

Topography and Culture

For topographical description the quadrangle can be considered under four headings:

The Berkshire Hills,
The Carbonate Belt,
The Slate Hills, and
The Claverack lowland.

(1) The Berkshire Hills represent the southern extension of the Taconic Mountains and just enter the Copake quadrangle at its eastern border about 3 miles north of the village of Copake Falls (shown as Copake Ironworks on the map). Immediately to the south they extend about 2 miles westward into the quadrangle but southward they gradually recede eastward, maintaining a distance of about half a mile within the eastern border. The New York-Massachusetts line runs along the crest of the range.

The Berkshires present a steep front to the west with a relief of about 1000 feet; Washburn Mountain attains an elevation of 1548 feet, Alander Mountain of about 2243 feet, and the lowlands lie at an average elevation of 500–600 feet. They are loftier eastward in Massachusetts.

The range is broken by few transverse valleys; the valley of Bashbish Brook makes a marked break east of Copake Falls. The hills are thickly wooded and have steep slopes, so that access is difficult. The only road crossing the range in this area makes use of the Bashbish valley, though Route 23 passes through Hillsdale and crosses the range northeast of the map area.

These hills are composed mainly of schist in this area, with some crystalline limestones at their foot and in the valley bottom east of Washburn Mountain. This valley is the only cultivated land breaking the general ruggedness of the Berkshire terrane in this vicinity.

(2) The carbonate belt lies west of the Berkshires. It is low lying, trends roughly north-northeast, and is underlain mainly by carbonate rocks. Its relief is low, and the topography is gently undulating; it is broken by small steep-sided hills such as Old Croken and Tom Hill northeast of the town of Copake. Average relief is 50–100 feet, and elevation is about 600 feet.

Where it enters the quadrangle in the south the belt is about 2 miles wide; it trends northeast to near Smith Hill where it widens to about 5 miles. It continues north-northeast, and tapers gradually until near Hillsdale it is reduced to a width of about a mile. Farther north it widens again as it passes northeastward out of the quadrangle.

The carbonate belt represents the main area of cultivation in the Copake quadrangle, though much of it is pasture land. A large part is flat and alluvium-covered and in many places swampy. The form of these alluvial areas suggests that many are residual glacial-lake bottoms or grossly overwidened valleys. Many of the lower hills, particularly along the foot of the Berkshires, are composed of Quaternary deposits and possibly represent deltaic deposits of outwash from the uplands.

(3) The Slate Hills lie west of the carbonate belt. These form wooded and fairly rugged country, though the relief is only about 300 feet. The belt extends to the western border of the quadrangle, except for a small triangular area in the northwest corner.

This belt is dissected by many small streams and contains several large residual lakes, notably Lake Copake and Lake Charlotte (now known as Lake Taghkanic), whereas most of the wider bottoms, particularly near the village of Taghkanic, clearly represent former lakes.

Glacially smoothed rock surfaces are common

in this area, and the valleys are filled with unconsolidated deposits. Cultivation is not widespread, though scattered farms in the valleys take advantage of drift fill. Most of the area is thickly wooded.

(4) The Claverack lowland forms part of the Hudson Valley flood plain. Its general flatness is broken by swarms of well-developed drumlins. This area is well cultivated, mainly for fruit farms.

DRAINAGE: The main streams of the area—Roeliff Jansen Kill in the south, Taghkanic Creek in the central part, and Claverack Creek in the north—flow westward into the Hudson River. Roeliff Jansen Kill flows parallel to the general structure in the northeast, from Hillsdale to the vicinity of Tom Hill, where it turns southwest and cuts across the structures. In the extreme south, near Mount Ross, it turns sharply north of west and cuts across, almost normal to the strike.

Taghkanic Creek and Claverack Creek are transverse streams for most of their courses. Bashbish Brook, on emergence from its sharp, east-west valley in the Berkshire Hills, turns south and remains a longitudinal stream for the rest of its course in the Copake quadrangle.

These main streams are fed by many minor tributaries with no marked pattern, probably of recent post-glacial origin. The form of the main water courses, however, particularly Roeliff Jansen Kill, suggests that they have been superposed.

The profiles of the Berkshire Hills show well-marked changes of slope and erosion levels apparently unrelated to lithological variations. These erosion levels can probably be correlated with those studied in New England (Pond, 1928; Meyerhoff and Hubble, 1928).

The area is thickly covered with glacial deposits; kames and drumlins are common, particularly in the lower elevations. Many of the hills show thick sand and gravel up to about 30 feet on their lower slopes, and yet on the crests of many solid rock is exposed.

General Geology

The three geological terranes of the Copake quadrangle correspond to the first three topographical divisions—the slate belt, occupying the western two-thirds of the area; the carbonate belt, containing mainly limestones and dolomites; and the schists of the Berkshire Hills. The average strike of these belts and of the rocks composing them is north-northeast, and the rocks apparently dip eastward. Thick glacial deposits obscure boundaries between rock units. Fossils are rare or absent, and the similarity between units, both of the carbonate sequence and of the slates, render lithological correlations difficult at first. Owing to the heavy glaciation and vegetation, lack of sharp lithological differences, and structural complexities, interpretations of the structure and of the stratigraphy are even more interdependent than in areas where the rocks are more extensively exposed.

The field work for this paper was carried out from early 1950 until late 1952. Mapping was done on transparent overlays attached to aerial photographs to a scale of approximately 3½ inches to the mile, subsequently transferred to a topographical map of the scale of 1/62500. A structural map (Pl. 4) is also presented. On the geological map glacial deposits and alluvium have been indicated by separate colors only in areas where they are so thick that they obscure the underlying solid rock and render inferences concerning boundaries undesirable. It is not to be inferred that there are not considerable unconsolidated deposits elsewhere.

To facilitate accurate reference to locations, the following method suggested by Rich (Bucher, personal communication) has been adopted. Five-minute meridians divide the map into nine rectangles (Fig. 2a). All locations are given in tenths of an inch from the north and west boundaries of the rectangle in which they occur. To locate these points, mark the right and lower edges of a piece of thin cardboard in inches and tenths measured from the lower right-hand corner. If this is placed on the appropriate rectangle with the south reading on the north boundary and the east reading on the west boundary, the required point will be under the lower right-hand corner of the card (Fig. 2b). This method could be used for all U. S. Geological Survey maps of whatever scale. For permanent use a scale can be made by incising the marks on the edges of a rectangle of thin transparent plastic.

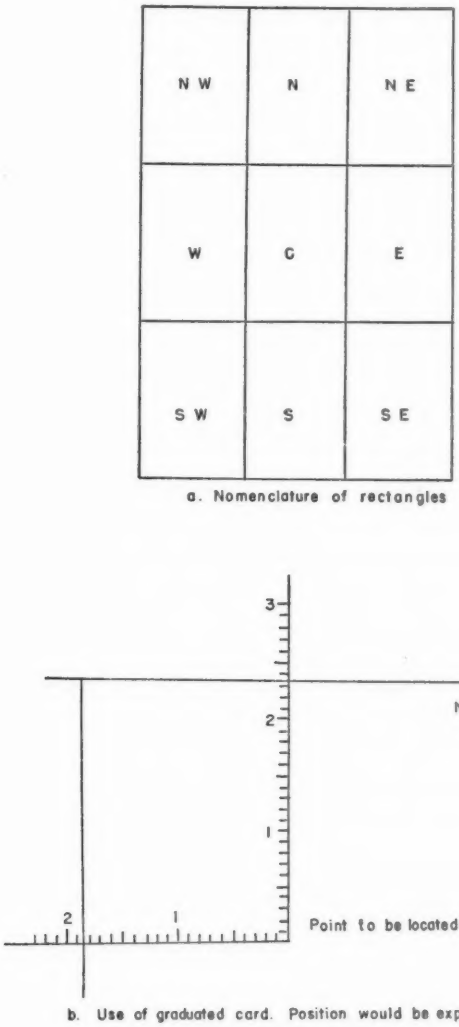

FIGURE 2.—METHOD OF LOCATING POSITIONS

STRATIGRAPHY

Carbonate Rocks

Pine Plains Group.—No complete section of the rocks of this group is found in the area, but the group constitutes much of the carbonate belt. It is a heterogeneous group containing dark-gray, fine-grained dolomites, sandy dolomites, oolitic dolomites, quartzites, edgewise conglomerates, and shales.

It has not been possible to subdivide the group, owing to the uncertainty of structural relationships between one outcrop and the next.

The most characteristic rock of the group is a dark-gray, compact, fine-grained dolomite, which weathers to a dark-rusty-brown surface with a rough hackly appearance, probably because of an irregular cleavage. The purity of the dolomite varies considerably, but in general sand content is high. The best continuous sec-

tion is seen on a grassy hillside immediately northeast of Ancramsdale (S44S41E; shown as "Ancram Lead Mines" on Plate 1). Here, about 400 feet of very variable dolomites interbedded with thin sandy beds and thin shales are exposed. Very thin (an eighth of an inch or less) crenulated sandy layers, characteristic of these rocks, stand out on weathering. Locally these thin layers have been broken up penecontemporaneously and give rise to local edgewise conglomerates, which pass laterally into continuous layers. Small masses of *Cryptozoon* were found in small outcrops just west of this; the layers are evidently associated with algal deposits (Pl. 2).

In the hill to the south (S55S34E), approximately 600 feet of hard siliceous dolomites must be present, but only about 50 feet is observable in scattered ledges. The exact relationship of this more siliceous sequence to the more dolomitic sequence is not evident, as the two appear to be separated by a fault. The more siliceous sequence may be older and has been brought up on a reverse fault, indirect evidence for which is found at the abandoned lead mine in Ancramsdale (S46S38E). The only other locality where this hard siliceous dolomite is found is in Old Croken about 2 miles to the north-northeast where again it is brought up on a reverse fault and overlies younger dolomite, resembling the Briarcliff dolomite.

At (S46S37½E) a ledge of hard greenish-gray quartzite approximately 20 feet thick is exposed across the field northwest of the lead mine. It is clearly a part of the Pine Plains sequence and is of some significance in the correlations which will be discussed.

In a field northeast of Ancram at (S15S22E) a 15-foot layer of an extremely hard, pure, dark-brown, vitreous quartzite is interbedded with dark-gray, fine-grained dolomite.

On the roadside northwest of Snyder Pond (E40S1E) a small exposure of a dark, blue-gray, oölitic dolomite is found. Top and bottom are not seen, but 6–8 feet is the probable maximum thickness.

In the more northerly outcrops of this formation, north and northeast of Hillsdale, some light-buff, sandy dolomites are found; the best exposure is at a road cut east of Hillsdale along Route 23, at (NE47S41E), and in the field to the south. The ridges north of Hillsdale at about (NE33S37E) also display well these buff-colored, sandy dolomites, which in places show strong, fine cross-bedding.

At these localities the subdivision of the Pine Plains group are best observed. The relationship between them is not evident in this area, as it is in the Millbrook quadrangle to the south, where the type section is located south of the town of Pine Plains. Knopf (1946) named the formation, but only a generalized description has been published so far. The presence of heterogeneous lithologies associated with much of the very dark-gray, compact dolomite distinguishes it from other carbonate units.

The Pine Plains formation as defined by Knopf is the lower part of what was formerly correlated with the Hoyt limestone in the Saratoga region. The correlation is based largely on lithological similarity in the Wappinger Valley, near Poughkeepsie, where Dwight (1886) found fossils characteristic of what was then considered Potsdam, but is now separated as Hoyt limestone. Knopf (1927, p. 437) lists the fossils as *Cryptozoon*, *Lingulella acuminata*, *L. minima*, *Obolella prima*, *Pelagiella* sp., *Saratogia calcifera*, var., *Plethopeltis saratogensis*, and *Dikellocephalus* (?) cf. *hoyti*, which represent a revision by Ulrich of Dwight's original identifications. Dwight's description suggests that the fossils were found in that part of the Hoyt which Knopf now designates Pine Plains. Knopf does not mention any fossils in the Pine Plains rocks, other than *Cryptozoon*. These also occur in the Copake quadrangle at Ancramsdale (S44S40E) and in the new road cuts for Route 22 north of Copake at (E32S29E).

Lithologically the Pine Plains formation strongly resembles the Danby formation of western Vermont (Cady, 1945, p. 535), particularly in its more sandy phases, and correlation of the two seems reasonable; they appear to be equivalent to the Franconia or middle Upper Cambrian.

The thickness of the Pine Plains is given by Knopf (1946, p. 1212) at 1300 feet at the type locality. In the Copake area no complete section is found. At Ancramsdale a section measures 406 feet. The hill at (S55S34E) must contain about 600 feet of the section, which

possibly underlies the first. In view of isolated outcrops containing lithologies not found in these two sections, the thickness quoted by Knopf for the type area probably exists here too.

Details of Exposures

(1) Ancramsdale (S44S41E), the best continuous exposure

Top

(Feet)	
39	Buff-weathering dolomite with thin sandy layers, some showing crenulations
14.3	Covered
0.6	Medium-gray, medium-grained dolomite, with many fine argillaceous layers
5.8	Covered
5.0	Dark-gray, fine-grained, buff-weathering dolomite
6.9	Fine-grained, dark-gray dolomite with thin shaly partings
28.2	Covered
11.7	Fine-grained, dark-gray, buff-weathering dolomite, well-bedded in 4–6 inch beds, with thin, sandy layers
14.4	Similar, but fewer sandy layers
20.9	Covered
5.8	Dark-gray, fine-grained dolomite with crenulated, sandy layers
9.7	Covered
4.3	Coarse-grained, medium-gray dolomite with sandy layers
1.2	Dark-gray, fine-grained dolomite
83.2	Covered
0.3	Very fine-grained, light-gray dolomite weathering a buff gray
11.8	Covered
40.6	Fine-grained, dark-gray dolomite, weathering buff, with criss-cross depressions on weathered surface, probably controlled by cleavage and giving a characteristic "rugged" appearance to the rock
58.9	Covered
1.8	Fine-grained, dark-gray dolomite, weathering massively
6.1	Covered
3.7	Thin-bedded sandstone becoming more massive above
7.5	Fine-grained, dark-gray dolomite, with crenulated sandy layers
23.6	Covered

Bottom

406 feet

Part of this section is exposed in a fresh road cut in the village of Ancramsdale, at the southwest end of the hill. In a fresh exposure the dolomites have a bluish, steel-gray tinge which distinguishes them from the weathered exposures even if the latter are broken with the hammer.

This section is presumably continued downward in the ridge to the west. At (S46S37E) is exposed a ledge of a hard greenish-gray quartzite which must belong to a lower part of the formation.

(2) Road cut on Route 23 about 1 mile east of Hillsdale at (NE47S41E)

Top

(Feet)	
5.3	Light-buff, very fine-grained dolomite, well bedded
11.0	Light-gray, rather sandy dolomite weathering to a rugged, dark-brown appearance, with quartz veins at base
10.6	Light-gray, very fine-grained dolomite becoming sandy toward the base
15.0	Dark-gray, fine-grained, buff-weathering dolomite

Bottom

41.9 feet

At (NE49S42E) in the field southeast of this exposure is a small quarry displaying 30 feet of fresh, medium-grained, dark-bluish-gray dolomite similar to that in the fresh exposure in Ancramsdale.

At the east side of the road at (NE55S43E) 50 feet of a light- to medium-gray, medium-grained, sandy dolomite, weathering to a rough, dark buff is exposed.

(3) Strong ridge about 1½ miles northeast of Hillsdale at (NE33S37E)

Toward its northern end, a 50-foot exposure of massive, medium-grained, dark-blue-gray dolomite, passing into sandstone above. About 50 yards farther south and apparently underlying this the following section is seen in a small cliff:

Top

(Feet)	
4	Thin-bedded, white, dolomitic sandstone, finely cross-bedded in parts
2	Medium-grained, dark-gray dolomite
3	Coarse sandstone, cross-bedded in parts
3.8	Fine-grained, gray dolomite, thin-bedded
3	Massive, medium-grained, medium-gray dolomite

Bottom

15.8 feet

The structure at the top of this hill indicates that the upper part is thrown into small folds; a zone of shearing in the first-mentioned exposure suggests that there may be some overthrusting here. Consequently the stratigraphic relationship between the two exposures is doubtful.

(4) Exposure of dark-blue-gray, oölitic dolomite, just north of Snyder Pond at (E40S1E) (already mentioned)

(5) Northeast of Ancram at (S15S22E)

15 feet of a hard, dark-brown, vitreous quartzite exposed overlying a fine-grained, dark-gray, buff-weathering dolomite.

(6) About a mile north of Copake at (E32S29E)

Blasting operations for straightening Route 22 uncovered a short section in these rocks. This will probably be covered again very shortly. The section measured here was as follows:

Top

(Feet)	
3.0	Coarse, dirty, dolomitic sandstone containing clay pebbles passing upward into a silty, dark-gray dolomite
6.1	Covered
12.5	Dark-gray, fine-grained dolomite, thin-bedded (1–3 inches), with fine, sandy layers
7.6	Covered
7.6	Mainly covered, but float indicates lithology similar to that below
7.6	Massive, fine-grained, dark-gray dolomite with irregular brownish blebs probably of organic origin

Bottom

44.4 feet

Some pieces of *Cryptozoon* material were found; some fine-grained, black, phyllitic shale was also passed through and probably belongs a few feet above this section.

Description of Thin Sections

(1) Slide No. CO 9—Locality SE12S19E. This rock is a poorly sorted sandstone, consisting of rounded to subangular, with some angular, grains of quartz, ranging in size from about 1.0 to 0.1 mm, in a fine-grained, siliceous groundmass. The latter shows some sign of recrystallization, in particular around the edges of pyrite crystals, where elongate, radiating crystals of quartz are normal to the surface of the cubes. Since this relationship exists regardless of the orientation of the pyrite, either the growth of the pyrite crystals set up stresses that controlled the direction of the recrystallizing quartz, or the pyrite was already present when the quartz recrystallized and caused local reorientation of the stresses arising from external pressure. Similar examples have been described (Fairbairn, 1949, p. 54; 1950) and referred to as pressure shadows. The interpretation made by Fairbairn is that the quartz recrystallizes on the protected side of the porphyroblast. In the case under consideration it is uncertain whether the orientation of the feathers of quartz indicates any rotational movement or not. The feathers occur on the faces of two pyrite crystals which are at an angle to one another. This tends to rule out rotational movement. On the other hand, the pattern is not so uniform as that illustrated by Fairbairn (after Pabst, 1931) as indicating nonrotational stresses. Some of the fine-grained groundmass also displays scalloping into the edges of the quartz grains. Some calcite and sericite are also present as well as large pyrite cubes (about 1.5 mm). Minerals present are: quartz 98 per cent, microcline 1 grain, muscovite, biotite, plagioclase, calcite about 1.5 per cent; the remainder is secondary sericite and pyrite. In hand specimen, the rock is a grayish-brown quartzose sandstone, approaching quartzite in appearance. It is fairly coarse-grained. Some disseminated pyrite cubes can be seen.

(2) Slide No. CO 11—Locality E25S30E. This rock consists essentially of dolomite with a large proportion of quartz grains intermixed. There is a definite orientation of the material which brings out the bedding. The average grain size of the carbonate, which is crystalline, is about 0.2 mm; the quartz grains range from about 0.01 to 0.2 mm. Most grains are subangular, but there has been some apparent recrystallization, and some of the slight rounding may be a result of this. Some carbonaceous impurities are present, gathered into wispy, dusty bands which swirl around quartz grains and suggest flowage. A small amount of microcline is present. Many of the quartz grains show strain. Minerals present are: dolomite 50 per cent, quartz 45 per cent, microcline, orthoclase, plagioclase (albite-oligoclase) 2 per cent, sericite 2 per cent, muscovite, rutile, zircon, pyrite 1 per cent, and traces of carbonaceous impurities (proportions estimated). In hand specimen, this is a medium-gray, sandy dolomite, showing streaks of black material which appear to be drawn-out shale fragments. Cubes of pyrite on the surface appear to have been elongated.

(3) Slide No. CO 10—Locality S12S23E. This is a well-sorted quartzose rock; rounded to subangular grains. There are two average grain sizes—about 0.75 and 0.1 mm. Little or no interstitial material is present; some extremely finely divided impurities included in the quartz grains appear to have been drawn to the edges, particularly toward the corners, and seem to merge with the very thin "skin" of such fine material between the grains. It also contains some fine sericite. In some cases, scalloping on the edges of adjacent grains indicates, together with the other evidence, that there has been some recrystallization. Minerals present are: quartz 99 per cent, zircon, biotite, microcline, feldspar, secondary sericite, minute quantities. In hand specimen, this is a hard, purplish-brown, even-grained, medium-textured quartzite.

(4) Slide No. CO 29—Locality S46S37E. A strongly quartzitic rock containing 91 per cent quartz, 1 per cent plagioclase; the remainder is fine-grained groundmass mainly of fine quartz and some sericite and chlorite. It is ill-sorted, and the grains are angular to subangular; grain size on the average is about 0.4 mm. There is some apparent granulation, and much of the quartz exhibits strain polarization. Interfingering of grains indicates recrystallization. A feldspar crystal is observed fractured and traversed by a finger of quartz which is continuous with a neighboring grain. Other minerals present include zircon, pyrite, chlorite, and sericite. The plagioclase is approximately oligoclase. In hand specimen, this is a hard, gray quartzite, with a

slight greenish tinge. It is medium-grained and lithologically is identical with the quartzite described subsequently as "gray-green quartzite".

(5) Slide No. CO 15—Locality N33½S36E. A medium-grained quartzite consisting of about 98 per cent quartz. Grain sizes may be grouped about two averages, 1.0–0.25 mm and 0.1–0.01 mm. Many of the grains show sutured contacts, and there is some granulation. One or two feldspars are present with very vague twinning which gives the impression that they were in process of alteration. A very small amount of interstitial calcite is also present.

Undifferentiated Cambro-Ordovician rocks.—The stratigraphical table based on Knopf's work in the Millbrook quadrangle (Knopf, 1946, p. 1212) shows three formations above the Pine Plains formation: the Briarcliff dolomite (1000 feet—Upper Cambrian), the Halcyon Lake calcitic dolomite (350 feet—Lower Canadian), and the Rochdale limestone (400 feet—middle Canadian).

Lithologically these formations are similar, and they are not sufficiently well exposed in the Copake quadrangle to be mapped separately. Many isolated outcrops must belong to one of these formations, but in the absence of fossils and well-defined lithological characters no differentiation was attempted. A considerable thickness of these rocks has been cut out in this region, owing to the widespread unconformity of the Black River-Trentonian and the overthrusting within the lower carbonate rocks. Extensive drift and alluvial cover in the carbonate belt also contribute to the apparent absence of rocks of these formations.

Several exposures can be tentatively allocated to one of these formations:

(1) The ridge running southward from Halstead (about SE43S39E) has some poor exposures of a medium-grained, dark-gray dolomite weathering to a light gray, which contains some crystalline quartz in irregular vugs. Cavities containing quartz crystals are characteristic of the Little Falls dolomite and also of the Briarcliff dolomite (Dr. W. Goldring, personal communication), and these rocks may be of Briarcliff age.

(2) A road cut at the western base of Old Croken (SE21S5E) shows 15 feet of well-bedded, medium- to light-gray dolomite; a similar rock crops out farther north at the road junction at (SE11½S10E). The former contains a thin, irregular, brecciated zone. These outcrops bear a strong resemblance to the outcrops of Briarcliff dolomite in the Pine Plains region.

(3) A railway cut at (E15S32E) displays 12 feet of a massive-bedded dolomitic limestone, light to medium gray and containing many calcite vugs and some crystalline quartz. This and the general appearance suggest Briarcliff age.

The Rochdale limestone is calcitic through a large part of its thickness and commonly contains *Lecanospira*. Below the base of the Copake limestone at Tom Hill (E40S22E) is a massive, medium-grained, light-gray dolomite weathering to a light buff or white and commonly containing chert in a curious lacy pattern. From its stratigraphical position this is assumed to be Rochdale limestone, though the lithological correspondence is slight. There is probably an unconformity below the Copake limestone, and possibly the Rochdale is not exposed in this area.

Copake limestone.—The type section for the Copake limestone is exposed at the southern end of Tom Hill (E40S23E) northeast of the town of Copake. Unfortunately the top cannot be seen. The upper part of the section is well exposed in a small quarry near the junction of Route 22 and the road leading into the town. The base of the section is seen in a series of small cliffs about 500 feet west of the main quarry. They are best approached through the yard of the Copake Lumber Company, though they can be approached through the field west of the quarry. Here the following section can be seen:

Top

(Feet)	
3.6	Medium-grained, medium- to dark-gray dolomitic limestone; toward the bottom, lighter and darker gray mingle to form a "flamelike" pattern
4.2	Fine-grained dolomitic limestone with irregularly scattered lenses of black chert
18.1	Massive, medium-gray, medium- to coarse-grained dolomite, becoming slightly finer-grained upward; thin calcite veins
100 (approx.)	Covered; scattered outcrops indicate massive, medium-grained, light- to medium-gray dolomite, weathering to a light-buff or white surface

5.6	Medium-grained, medium-gray, white weathering dolomite
5.8	Medium-grained dolomite with faint laminations
8.0	Medium-grained, sandy dolomite with some very sandy layers; gastropods occur on deeply weathered, reddish-brown sandy surfaces as casts; doubtful worm borings also present; cross-bedded
6.3	White-weathering, slightly sandy dolomite containing worm borings
3.8	Slightly sandy, medium-gray, cross-bedded dolomite
3.3	Coarse-grained, medium-gray, white-weathering dolomite
3.5	Gray-weathering, silicified dolomite
2.5	Medium-grained dolomite with some cross-bedding, fairly thin-bedded
22.3	Coarse-grained dolomite with sandy layers
25+	Coarse, medium-gray, sandy dolomite with some cross-bedding

Bottom

212.0 feet

The most conspicuous distinguishing characteristic of the Copake limestone is the 80–90 feet of sandy dolomite with cross-bedded layers which forms the base of the formation and is easily recognized in isolated exposures, particularly where the cross-bedding has been etched by weathering.

The upper part of the formation is more calcitic than most of the underlying carbonates. The weathered surfaces of small exposures resemble dolomites of the Briarcliff and Rochdale formations.

Except for *Cryptozoa* in the Pine Plains, these rocks are the oldest in the quadrangle in which definite fossils have been found. Unfortunately they are not sufficiently well preserved for specific identification. They consist of external molds of a planispiral gastropod (about an inch in diameter) which may be *Ophileta* sp. The late Dr. Josiah Bridge thought they were probably of late Beekmantown age. Knopf (1927, p. 438) reports *Ophileta* sp. from the Copake limestone but does not mention the locality.

Dwight (1901, p. 490) discovered *Syntrophia lateralis*, *Eotomaria* (?) *cassina*, *Isoteloides* sp. in Dutchess County, south of Copake, but did not mention localities. He correlated the fauna with that of the Fort Cassin beds in Vermont on the basis of the trilobites, though he notes the absence of the cephalopods that are characteristic of the true Fort Cassin. Rousseau Flower (Personal communication) considers that the Copake limestone is to be correlated with the Fort Cassin and draws attention to the characteristic sandy basal beds. Evidence in this area attests to this correlation.

The term Copake limestone was first used by Dana (1879, p. 376) as a terrane term for all the limestone in the Copake area. Knopf (1927, p. 438) first used the term with a stratigraphic significance.

Owing to the structural complexity and to the absence of diagnostic fossils, accurate stratigraphic definition of the term is difficult, but Copake limestone may be defined as a series of dolomitic limestones with about 90 feet of irregularly cross-bedded, sandy dolomites at its base and containing worm borings and a planispiral gastropod resembling *Ophileta*. Its thickness is unknown, since the top contact is not seen. Not more than 212 feet is present in the type section. Knopf (1927, p. 439) states that there is 400 feet present in the Millbrook quadrangle. Another section there might better serve as type.

Microscopic examination of the sandy plase at the base of the formation shows that the rock contains about 60 per cent carbonate and that the remainder is chiefly quartz with about ½ per cent plagioclase (albite-oligoclase) and microcline. Grain sizes range from an average of 0.2 mm for the carbonate to 0.01–0.1 mm for the detrital quartz. This suggests that the detrital material was derived from a metamorphic terrane. Measurements on the cross-bedding are not easily made, but the general trend of the fore-set beds suggests derivation from the west; average direction of dip is N. 80° E.

Pyrite is scattered through the formation, and in parts a strong odor of H_2S is given off when the rock is broken.

Details of Exposures

(1) The best exposure of this formation is at Tom Hill, Copake (E40S23E), which has already been described and is adopted provisionally as the type section (Fig. 3).

(2) The sandy lower horizon can be traced for some distance southward along the eastern side of Bashbish Brook from (E49S20E) until it finally disappears under the overlying black shale.

Black River-Trenton limestone.—At the Tom Hill section the Copake limestone is overlain by the following:

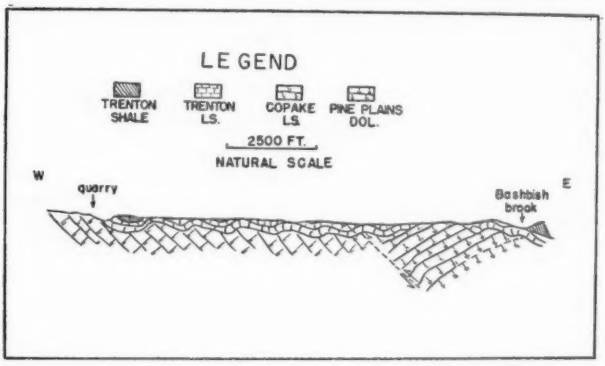

FIGURE 3.—CROSS SECTION EASTWARD FROM TOM HILL, COPAKE

Top		Black shale
	(Feet)	
	4	Thin-bedded, argillaceous, blue-gray, fine-grained limestone
	6	Thin-bedded, blue-gray limestone with white dolomitic bands; lenslike occurrences of thickly scattered, fragmental organic remains, chiefly echinoderm plates with some gastropods and possible cephalopod
	14.7	Thin-bedded, blue-gray limestone with very thin sandy partings
Bottom		
	24.7 feet	

These rocks occur at the top of the section in the quarry at Tom Hill and are traced across the road (Route 22) eastward into the bed of the Bashbish Brook. Traced northward along the brook, they pass upward into black shale, with two limestone bands, the first 18 inches thick and the second 4 inches thick, separated by 3 feet of shale, occurring in the shale about 25 feet above the top of the main limestone.

At first this formation was thought to be conformable above the Copake limestone. The contact can be seen well at the Tom Hill Quarry and is clearly depositional. However, as mapping progressed a strong regional unconformity beneath it became evident. This is found almost everywhere along the eastern margin of the shale belt below the black shale, resting in some places on Pine Plains rocks and in others on the Copake limestone.

It is interpreted therefore as a basal limestone formation of the black-shale sequence, present only where the latter overlies the carbonate belt. It probably corresponds to the Whipple marble in Vermont (Fowler, 1950, p. 32).

It is not everywhere continuous, perhaps owing to nondeposition or erosion, or merely to local faulting. For example, southward from Copake along the east side of the Bashbish Brook (E29S20E) the base of the Copake limestone disappears under the black shale east

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PLATE 2.—TYPICAL OUTCROPS AND STRUCTURES

FIGURE 1.—Typical exposure of Pine Plains dolomite at (S44S40E) near Ancramsdale, showing the characteristic irregularly crinkled thin sandy layers.

FIGURE 2.—Exposure in Trenton limestone at (NE38S31E), about a mile North of Hillsdale, showing a small westward overturned anticline and well-developed axial-plane cleavage. A harpid trilobite was found on the crest of the fold.

FIGURE 3.—Black Trenton shale, to the east of Green Hill, showing the small-scale crumpling.

FIGURE 1

FIGURE 2

FIGURE 3

TYPICAL OUTCROPS AND STRUCTURES

FIGURE 1

FIGURE 2

FIGURE 3

FIGURE 4

FOSSILS

of it. The cross-bedded sandy dolomite characteristic of the basal Copake can be seen within less than 10 feet of the black shale, and there is no room for the limestone between. Very possibly the limestone was faulted out, as this section is along the line of the strong reversed faulting which brings Pine Plains against Copake limestone.

In most places the lower contact of the black shales is masked by Quaternary deposits; the limestone may be missing, though in most areas its presence is suggested. Around the lenslike outcrop of black shale extending southward, southeast of Halstead (SE43S14E), in places the dolomite of Copake type occurs so close to the black shales that it makes the presence of the limestone improbable.

Local unconformities probably separate the limestone and the black shale. The unconformities must be slight, however, since the limestone passes upward transitionally into the shale both at Tom Hill and on the east side of Smith Hill (SE30S3E).

The formation is the most fossiliferous carbonate rock in the area, and lenses in it are packed with organic remains, yet the fossils are not diagnostic. The most prominent fossils are echnioderm plates (probably mostly cystids), few of which are specifically identifiable. Gastropods are common but are too poorly preserved, chiefly as a result of recrystallization of the rock, to be identified. Certain cystoid plates show some unique features but do not assist in correlation, though they may be of value in recognizing the horizon in the future. The small notched cystoid (?) plates (Pl. 3) are comparable to similar better-preserved material from the Bromide formation of Oklahoma, now considered to be of Trenton age (Pl. 3). (The writer is indebted to the late Dr. Josiah Bridge for these samples.) Small oval plates, which are about 2–3 mm in diameter and have notches at either extremity of the long axis, are extremely common, particularly in the exposures along Route 22, east of Tom Hill. Circular stem ossicles with a trifoliate lumen are also common (Pl. 3). A doubtful pelecypod also suggests at the earliest a middle Ordovician age, whereas a harpid trilobite cephalon (Pl. 3) displays no diagnostic characteristics and does no more than suggest a Fort Cassin or later age (Whittington, personal communication).

The fossils indicate a Black River-Trenton age for the formation, and this correlation is proposed. Further subdivision would not be justified. This implies the absence of the Chazyan in the area. It is, therefore, possible that this limestone is of Chazyan age. The paleontological evidence is not very strong, but since this limestone is interbedded with the basal beds of the black shale, the fossils of which point to a Trenton age, a Trenton or possibly Black River age seems probable.

This rock is found almost everywhere at the base of the black shales where the latter are in contact with the carbonate belt. It is also found all along the western edge of the Berkshires underlying the schist. It is more recrystallized in the latter localities but is still recognizable and in places contains lenses full of echinoderm plates which, though now recrystallized, resemble lenses in the less recrystallized outcrops.

Details of Exposures

(1) The best outcrop of this formation lies in the roadside of Route 22, on the east side of Tom Hill (E39S24E). Recent road-widening operations have left much of the outcrop but removed most of the weathered surfaces. The fossils can be found only with the greatest difficulty on fresh surfaces. This whole section can be followed from the top of the Copake limestone quarry, at the south end of the

PLATE 3.—FOSSILS

FIGURE 1.—Slab of Trenton limestone from the east side of Tom Hill, Copake, showing various types of echinoderm plates: × 1½.

FIGURE 2.—Echinoderm Plates fom the Bromide formation, Oklahoma, for comparison with the notched plates in Figure 1: × 1½.

FIGURE 3.—Harpid trilobite, brim of cephalon, locality (NE38S31E), Trenton limestone: × 1⅞.

FIGURE 4.—Problematical marking in Elizaville Shale at Martindale: × ⅔. The branches can be seen to terminate sharply at the main stem, suggesting that it is not a trail.

hill, across the road eastward and into the valley of the Bashbish Brook where the upper argillaceous part is exposed in the stream bed. Near the base, in the quarry, good examples of contemporaneous crumpling are observed, with minute folds overturned westward.

(2) Good exposures are found in a field west of the road (NE38S31E) about a mile north of Hillsdale. Here the rocks are thrown into folds of an amplitude of 2 or 3 feet. In the more easterly exposures strong flow folding is found. Fossils were found in the more westerly exposures, including echinoderm ossicles and the cephalon of a harpid trilobite. The specimen was examined by Dr. H. B. Whittington who wrote, "I agree with you that your specimen is most probably the brim of a harpid trilobite. Regrettably no pits or other details are visible, but the outline is characteristic. This is about as much as one can say, except to point out that Whitfield (Bull. Amer. Mus. Nat. Hist., vol. 9, (1897, p. 182–183; Pl. 5, figs. 3 and 4) described '*Harpes cassinensis*' from the Fort Cassin of Vermont. This harpid is the oldest so far known to me in North America and it seems likely that yours is the same or a related species. The finding of a harpid in the Copake[1] does seem to confirm that it cannot be, at that locality, older than the Fort Cassin.

"I have used 'harpid' above to denote belonging to the family Harpidae. I do not think that Whitfield's species can be referred to *Harpes* s.s., but probably is a representative of my species *Selenoharpes* (Palaeontographical Soc., London, 1950, p. 10, etc.). I have referred a Swedish species, which is older than "*H*". *cassinensis*, to *Selenoharpes* also. I have not seen the type specimen of Whitfield's species, and until I do, would not want to confirm the generic reference".

This specimen was found in the crest of a small anticline where axial-plane cleavage is well developed. About 150 feet to the east the rock shows strong flow structures. Since the fossil was undisturbed in its external shape, the details of structure having been obscured by recrystallization, the flow folding probably took place before lithification.

(3) This formation is brought up in a long narrow anticline and can be traced from Chrysler Pond (C43S33E) to the southeast corner of Lake Copake (C20S43E). The best exposures are found near the ends. On County Road 27, at the northeast side of Chrysler Pond, just east of the fork between County Road 27 and 27a, the anticlinal structure is well exposed. In the field to the north, extensive ledges of the rock crop out; many contain echinoderm fragments. Here also a doubtful pelecypod was found. A little more than 400 yards eastward along the road, typical Pine Plains dolomite is exposed (Fig. 4).

On the north side of the road leading northeast-

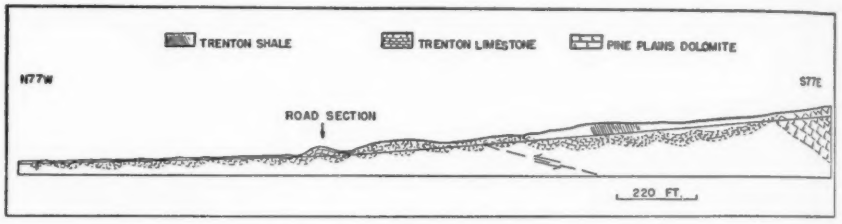

FIGURE 4.—EAST-WEST SECTION NORTH OF CHRYSLER POND—(C43S33E)

ward from the southeast corner of Lake Copake, and about 300 feet east of the lake, a road cut displays this limestone, more deformed and thrown into tiny dragfolds overturned to the west. No fossils were found here. The upper more argillaceous part, where exposed in a road cut, is easily mistaken for the black slate, since it is usually strongly cleaved, and, particularly if wet, the color is very similar.

(4) Exposures of this formation occur around the base of the black shale at Smith Hill (SE30S3E), particularly in the fields on its northeast side and along the road running along its east flank. Along this road about 200 yards south of the road fork, exposures show the limestone passing up into the black shale. This is one of the few well-exposed contacts in the area and is very significant, as it displays the gradation. The rocks were tested with dilute HCl, and samples were taken progressively higher; the carbonate content decreases from high to zero with no sharp boundary.

(5) East of Ancramsdale at (S46S36E), on Route 82, a road cut shows this limestone brought up in a small faulted anticline. Here a small gastropod (*? Cyrtolites*) was found. In the creek bed to the south, Pine Plains dolomite is found. The structure is complicated here and will be discussed below.

(6) A small quarry at (E2S39E) displays this limestone strongly affected by drag folding, the folds ranging from 1–2 inches to about a foot in amplitude and overturned to the west. Dolomitic bands show boudinage structure, with good transverse tension fractures.

(7) This limestone underlies the black shale on the east flank of Fox Hill at (SE54S27E) in a creek bed. Here it is more strongly recrystallized and is white. Thin bands of sandy material are comparable to those in the section at Tom Hill, and small lenses bear a strong resemblance to the echinoderm lenses.

(8) At the western foot of Alander Mountain at (SE2S33E) good exposures of a more strongly re-

[1] This was written when it was considered that this limestone was part of the Copake limestone.

crystallized blue-gray to white limestone are found, which is certainly the same formation. It contains fine sericitic partings and strongly marked bands on weathered surfaces which resemble the echinoderm lenses. Calcite fragments in cross section appear clearly to be derived from echinoderm plates similar to those found in the relatively unaltered rock farther east. These two can be readily correlated.

(9) Several exposures of these more altered limestones are found in an inlier on Masters Farm east of Washburn Mountain at (E43S39E).

Summary of carbonate rocks.—The carbonate belt contains rocks ranging in age from Late Cambrian to Middle Ordovician. The absence of good fossils throughout the section renders any long-distance correlation extremely tentative, but the evidence available indicates the following stratigraphic sequence:

			Estimated thickness (Feet)	
Mohawkian	Black shale Trenton limestone		25	
Canadian	Copake limestone		400	
	Undifferentiated			
	Cambro-Ordovician rocks	Rochdale Halcyon L. Briarcliff	1800	(?)
Late Cambrian	Pine Plains dolomites		900	(?)

From lithological comparisons with near-by areas where evidence is more satisfactory for correlation, the Pine Plains dolomites can be dated as middle Late Cambrian. Lithologically they appear equivalent to the Danby formation of Vermont.

The Copake limestone, on lithological grounds and tenuous fossil evidence, is correlated with the upper Canadian Fort Cassin beds.

The blue-gray limestone with fossiliferous lenses—the fossils are mainly echinoderm fragments—is basal to the overlying black shales. Any attempt at a more refined correlation in this area would have little supporting evidence. This limestone cuts across the underlying formations in a broad regional unconformity and underlies the Berkshire schist in the eastern part of the quadrangle.

The only unconformities noted in this area are the strong one below the Trenton limestone and possibly slight unconformities between it and the black shale. The basal sandstone of the Copake limestone also suggests an unconformity of unknown magnitude.

Shale Belt

General.—The western two-thirds of the quadrangle is underlain by slates or shales which fall within the general terrane term Hudson River shales. In this area they have been divided into two major groups, the Elizaville shales and the Trenton black shales (Pl. 1). As elsewhere in the area, the stratigraphic relationships are obscure and depend largely on the structural interpretation.

Four mappable units can be recognized in the slate belt:

(4) Trenton black shales
(3) Calcareous grit
(2) Gray-green quartzite
(1) Elizaville shales

Because the details of structure are even more obscure in the shales than in the carbonates and because upper and lower contacts are nowhere located, thicknesses are approximated and may be in error by hundreds of feet.

Elizaville shales.—The name of these shales is taken from the village of Elizaville in the southeast corner of the Catskill quadrangle; these rocks are well exposed near there.

These shales extend north-northeastward in a belt about 3 miles wide from the southwestern corner of the quadrangle. The unit is mainly light gray but ranges from a light-greenish gray to a dark gray approaching black. It has a rather coarse shaly or fine silty texture, but there are all variations from fine phyllitic shale to coarse siltstone.

In the upper part it contains a horizon with many bands of brown quartzite ranging from 3 inches to 12 inches in thickness, at intervals of 2 or 3 feet. The exact stratigraphic position of these quartzites in the formation cannot be determined, but it seems reasonable to place them in the upper part, since they occur on either flank of the belt which is interpreted as of anticlinorial structure.

In a fresh exposure, the shale is in places laminated in bands of slightly darker and slightly lighter gray material; the bands are a few millimeters thick. This lamination is not present throughout, however. The banded rock is probably near the middle of the sequence. In the same zone irregular blebs of black carbona-

ceous matter are common and seem to be of organic origin.

Another type of banding consists of thin (1–2 mm) layers of ferruginous and dolomitic material an inch or so apart and characterized by a fine irregular crumpling, with crenulations of amplitude about half an inch. The crenulations do not conform to one another from layer to layer—that is, an "anticline" in one layer is not necessarily related to one in the layer above or below. The crumpling is reminiscent of the irregular crinkling in the Pine Plains dolomites. It may be due to contemporaneous sliding or be associated with algal activity. Secondary processes could hardly have produced it, although the rock displays strong slaty cleavage.

In exposures of the more shaly lithologies, the rock is slightly greenish if viewed from a distance of a few feet, but this cannot be seen on close examination or in the hand specimen. No very good exposures were found of the red and green shales which are so widespread in the Hudson River shales in adjoining regions. A small road cut south of Philmont (N7S4E) does show some deep-red shale with interbedded layers of hard green siliceous shale, but it is a poor exposure, and its relationship to the other rocks cannot be seen, though it falls within the area of the Elizaville shale and is presumably part of the sequence. These red and green shales may be of local development, since they are strongly developed southwest of this quadrangle in the Rhinebeck quadrangle and are almost equally well developed to the north in the Kinderhook quadrangle. Of course, they may have been cut out by faulting or may be concealed beneath the unconformable Trenton shale in this quadrangle.

The rock is well cleaved throughout, and, particularly in new road cuts southeast of Churchtown, cleavage is so well developed that it makes possible the parting of large sheets. It is nowhere of good enough quality for commercial purposes, however.

A large road cut at Martindale on Route 23 (N29S17E) contains the only suggestion of recognizable organic remains in these rocks. It is an obscure curvilinear impression with straight branches at irregular intervals along its length. It shows traces of ferruginous material. It might be interpreted as a trail, but the branches would indicate otherwise. In over-all morphology it distinctly resembles the graptolite *Holograptus*, as figured by Elles and Wood (1918, Pl. VIII, fig. 2a), and though such an identification is very tenuous it seems the only reasonable one (Pl. 3). If this is correct, of course, it is extremely significant. It would suggest an Early Ordovician age for these rocks and thus corroborate other evidence.

Details of Exposures

(1) The best exposures displaying the typical lithologies of the Elizaville shale sequence are in fairly new road cuts made during the improvement of Columbia County Road 27, southeast of Churchtown.

At (W10S31E) a section shows about 48 feet of a hard, strongly cleaved, light-gray, fine-grained siltstone. A low-angle thrust can be observed at the northwestern end of the section, and on the upthrown side, which makes the main part of the exposure, the rocks seem to dip about 38° N. 63° E. The bedding in a few places is marked by thin sandy layers. There is some overturning close to the fault. In the vicinity of the fault, the slate shows thin bands of lighter- and darker-gray material. Irregular small patches of black carbonaceous material are scattered through the rock. Small concretions give rise to forms with a slight relief on cleavage surfaces, several of which have a four-rayed form like *Tetragraptus*. They seem to have an organic origin but are not believed to be graptolites. The whole is commonly traversed by thin veins of iron-stained calcite. Possibly these are derived from calcareous material originally present in the rock itself.

(2) Farther west along the road, toward Churchtown, are several exposures of this unit. Occasional 2- or 3-inch quartzite bands are interbedded. At (W7S28E) the following section is seen:

Top

(Feet)	(Inches)	
1		Brown, pure quartzite
4		Gray shale
1	4	Brown quartzite
2	9	Gray shale
	6	Brown quartzite
3		Gray shale
1–2½		Brown quartzite
		Gray shale

Bottom

The rocks dip 25° S. 84° E.

In small road cuts farther west, more scattered quartzite bands are found, and as the structure between is not exposed they may or may not be repetitions; some repetition is almost certain, since the observed structure consists of small overturned folds and low-angle reversed faults.

West of these outcrops, in the woods north of the road, the gray shales are overturned and overthrust over the black shales to the west. The structure is well brought out by the quartzite bands and can be seen in a series of cliffs at (W0S25E).

(3) At (N43S13E), on the south side of the trail crossing the woods in a westerly direction, is an exposure of 15 feet of banded gray shale with 1-foot bands of brownish quartzite as "boudinaged" lenses. The beds elsewhere in the vicinity are not well exposed but seem to have (10°) dips; small scattered exposures through the woods display quartzite bands about a foot thick.

(4) A large road cut on Route 23 at Martindale (N29S17E) gives a good section in disturbed gray shales and siltstones. Bedding is fairly well developed here as a result of banding of subtly varying lithologies; the exact nature of the variation is not usually evident, though it is probably due to slight differences in grain size. One thin quartzite band is interbedded. Owing to the structural deformation the thickness exposed can only be estimated, but since the beds are dipping at an average of 70° the length of the outcrop—190 feet—indicates that there is probably about 150 feet present. Two small faults, probably reverse faults, cut across the outcrop, and this would tend to reduce the thickness estimate. It is not possible to see the throw of the faults, but they appear to be minor. At this exposure the problematical fossil (*?Holograptus*) was found. The whole rock is strongly cleaved; this exposure is one of the few where westward dips are observed in this region.

(5) Other good exposures of the Elizaville shales without any other notable features, are found at (C31S6E) in the woods west of Harry Post's farm. Here they exhibit very strong crumpling and small chevron folds of amplitude approximately 1½ feet. At the falls on Taghkanic Creek at New Forge (W42S40E) these shales are also well exposed. Further good exposures of strongly crumpled gray shales with some quartzite bands are found at Green Hill at (SW26S18E), particularly on the western slope.

(6) An exposure in the bed of the Roeliff Jansen Kill south of Jackson Corners at (SW50S4E) gave occasional reaction to dilute HCl, indicating some slight admixture of calcareous material.

(7) At (SW5S18E) south of Lake Taghkanic (Charlotte Lake on the map), the rocks, as displayed in a road cut, are abnormally shaly and are greenish when observed from a distance. On closer examination, the color is light gray.

(8) At (N7S5E), south of Philmont, a poor road cut exhibits about 50 feet of reddish-purple fine-grained slate with irregularly interbedded light-green slate, which is somewhat siliceous. This is the only exposure in the area where these red and green slates are seen, and their relationship is obscure though they seem to be part of the Elizaville shale sequence.

(9) At (W17S40E) in a road cut on Route 27 (County Road) on the west side of the intersection about 10 feet of gray shale lies almost horizontal and is banded with very thin ferruginous-dolomitic layers about 1–2 mm thick and about an inch apart. These are strongly crumpled in minute folds of an amplitude of about half an inch. The folds from one layer to the next seem unrelated, and they were either formed by slight contemporaneous sliding or are associated with algal activity.

Gray-green quartzite.—This unit and the calcareous grit are both part of the Elizaville shale series, but since they are easily distinguished they have been mapped separately.

The gray-green quartzite is best displayed in the vicinity of the Pinnacle at (W6S34E). It forms here a prominent topographical feature. It is a massive, hard, greenish-gray quartzite. In general it is of medium grain size, but patches of fine quartz pebbles are scattered irregularly through it. At the Pinnacle 25–30 feet is exposed, though as usual the boundaries are obscured, and thickness can only be estimated. Some faulting is present. Nowhere else does this quartzite form such a strong feature, though it usually makes well-defined ridges.

The greenish color is due to extensive chlorite. In thin section most of the chlorite is of secondary origin, though a very little may be primary. It is most extensively developed near faults, and its origin seems to be connected with deformation. It is probably true that wherever the quartzite is exposed, it has been involved in faulting. The surrounding shales apparently have yielded to deformation by folding, whereas the harder quartzites have yielded by faulting.

The rock is a fairly pure quartzite, though there is a small percentage of feldspar and traces of zircon and tourmaline.

Ledges of identical rock are scattered throughout the Elizaville shale belt, though only a few outcrops approach the thickness of 25 feet.

The question arises whether all the quartzite ledges represent repeated outcrops of the same zone or whether they represent bands at different horizons. All the outcrops are discontinuous and cannot be traced far along the strike; however, most, if not all, the outcrops of this lithological type probably belong to a single band. This conclusion is based on (1) the uniformity of lithology of all the outcrops; (2) the scattered distribution of the outcrops which here would indicate irregularly disposed thrust slices of a single bed, rather than many beds at different stratigraphic levels. In the latter case the layers should be traceable more regularly along the strike. Significantly, this quartzite is indistinguishable from one interbedded

with the Pine Plains dolomites at Ancramsdale.

Details of Exposures

(1) The most extensive and typical exposures cap the conspicuous hills in the vicinity of the Pinnacle at (W6S34E). It is a massively jointed medium-grained gray quartzite, in which it is extremely difficult to determine bedding. The base, however, overlies a fine-grained dark-gray shale. There are two outcrops of the quartzite with gray shale between; they are separated by a fault. A minor reverse fault can be seen in the southern face of the northwesterly outcrop. On the whole the quartzite has yielded to deformation by reverse faulting, and the shale by asymmetrical folding, but where the lower contact is exposed the quartzite too is affected by rather gentle shallow folds of a wave length of 10–12 feet and an amplitude of about 2 feet. The maximum measured thickness here is 25 feet, but as the top contact is not seen it is probably somewhat thicker.

(2) A more accessible exposure is at (W17S40E) in a road cut at the intersection of County Road 27 and the dirt road leading northward toward Hollowville. Here the rock has the same lithology and overlies gray shales. Northward along the dirt road about a mile a continuation of the ledge shows strong signs of faulting—thick quartz veins with coarse breccia of quartzite fragments. These veins and breccias are particularly strongly chloritized. Again the top is not exposed, but not more than 20–25 feet is present.

(3) In a good exposure at (NW57S40E) the quartzite forms a pair of strong ridges trending north-south with gray shale between. This again appears to be due to repetition by reverse faulting, though no strong evidence can be seen. Here, on the extreme western face, the quartzite contains a conglomeratic lens with quartz pebbles about pea size. It is underlain by a dark-gray, almost black shale. The cleavage-bedding relations of the shale are obscure but at one place suggest overturning.

(4) Many other scattered outcrops show similar characters. At (N51S13E) a ledge contains about 15 feet of quartzite overlying dark-gray to black shale. Other outcrops are on the west side of Forest Pond at (N41S17E) and a smaller one at (N31S28E) to the east of Martindale where the thickness is not determinable, as the degree of dip cannot be observed; it is thought not to exceed 20–25 feet.

Description of Thin Sections

(1) Slide No. CO. 24—locality W5S32E. A closely compacted rock consisting essentially of subangular quartz grains with a little feldspar. The grain size ranges from 0.2 to 0.4 mm with some patches of much finer material. The slide is traversed by a vein of coarse-grained quartz. Much chlorite, most of which is vermicular and clearly secondary, is present. Minerals present are: quartz 91.2%, plagioclase 0.7%, orthoclase 0.1%, chlorite 1.2%; fine groundmass of quartz and chlorite and one or two chert fragments make up the remaining 6.8%. An isolated grain of well-rounded zircon and one of brown tourmaline were observed. The plagioclase again exhibits albite twinning.

(2) Slide No. CO. 27—Locality W17S40E. This section is very similar to the above except that there is a larger proportion of fine-grained material; 96.5% is quartz (56.4% $>$ 0.1 mm, 40.1% $<$ 0.1 mm), 0.4% plagioclase, 3.1% groundmass, much of which is chloritic. The rock is closely compacted with ill-sorted angular to subangular grains.

In hand specimen, these two rocks are very similar and consist of a hard, gray, medium-grained quartzite, with a slight greenish tinge owing to the presence of chlorite.

Calcareous grit.—This unit consists of a massive, dark-gray, fairly coarse, impure sandstone containing scattered calcareous material. In a few places it becomes very micaceous. Apart from the latter slight variation, it is fairly uniform in lithology and is easily distinguished; its main characteristic is its spotty reaction to HCl. It commonly contains flattish clay pebbles, about half an inch in length. One of the better areas of outcrop of this rock is in an anticlinal belt extending southwest from the vicinity of Pumpkin Hollow (C27S35E), where it is bedded with a dark-grayish shale. Farther southwest, a belt of outcrop extends down about a mile west of Ancram. Here and in the other larger outcrop area immediately to the northwest it occurs in a closely folded belt infolded with shales, and consequently the outcrop pattern on the map is generalized, as only scattered outcrops are found in the heavily wooded and brush-covered country. The top and bottom contacts are not exposed, and thickness is estimated not to exceed 25 feet.

The rock is thought to be a single unit and is everywhere uniform in character and appearance; it can be considered part of the Elizaville shale sequence, emerging through the black slates which cover the whole unconformably.

Details of Exposures

(1) Perhaps the best exposure of this rock is in a field north of County Road 27 at (C41S20E), where it is exposed in a well-defined anticlinal structure and plunges southwestward under the black slates. It can be traced northeastward into a cirquelike hollow in the hillside and it is exposed in a small road cut on the south side of the County Road. Farther northeast the structure can again be picked up at (C34S31E) and can be traced northeastward until it disappears under superficial deposits, south of Lake Copake. It is associated in these exposures with a gray shale similar to the typical Elizaville shale.

(2) About 1½ miles north-northwest of Ancram along Route 82, it is again exposed in a series of

ledges in fields on the northeast side of the road, in the vicinity of (S9S13E). Here the structure consists of close zigzag folds, and the rock is infolded with black slate. A careful search of all the outcrops disclosed no place where the black slate underlay the grit. In this area the grit is micaceous in places.

(3) At (SW4S35E), near Suydam the rock is exposed at an easily accessible place. It is overlain by black slates.

(4) The calcareous grit can be found in small patches southwestward from the extremity of the quadrangle where it is found at the top of the ridge west of Mount Ross.

(5) The rock is also found in small patches in the more westerly part of the area. At (NW47S10E) it is found in a road cut associated with black slate, which again appears to overlie it. Here a large boulder of the rock is found, separated from the main outcrop and embedded in black slate, the cleavage of which is bent around the boulder. The latter has fairly sharp uneroded edges. It is difficult to decide whether it represents a fragment broken off in subsequent faulting or whether it is a boulder spalled off into the transgressing black shale and therefore indicating an unconformity. It does seem that some stronger deformation would have been evident if it were a boudinage phenomenon, and the second alternative is preferred.

(6) At (NW38S15E) on the west side of the road this rock crops out in a small syncline where it appears to be about 4 feet thick. It is poorly exposed but is associated with a dark-grayish-green shale and is overlain, separated by about 20 feet of shale in the core of the syncline, by 10 feet of sandy dolomite which passes upward and laterally into a limestone conglomerate.

(7) On the north side of Lake Taghkanic at (W50S22E) a small road cut exhibits this rock interbedded with typical gray shale of the Elizaville shale type. The calcareous grit appears to be 40–50 feet thick here, but as it grades into the shale it is difficult to place the actual contact.

Description of Thin Sections

(1) Slide No. CO. 26—Locality C40S21E. A grossly ill-sorted subgraywacke, consisting mainly of quartz and calcite fragments with some feldspar and a considerable proportion of fine-grained groundmass, chiefly sericitic. The grains are angular to subangular, grain size ranges from 2 mm for the larger fragments to about 0.001 mm. Two large fragments of a fine-grained carbonate rock are observed, one with a suggestion of organic material. Most of the carbonate is detrital, but some may be recrystallized subsequent to deposition. Grains are apparently oriented parallel to the bedding. In this slide again there is the curious orientation of recrystallized quartz associated with a pyrite crystal, comparable to that observed in the Pine Plains sandstone, slide No. CO. 9. Minerals present are: quartz 34.8%, carbonate 7.5%, plagioclase 0.4%, pyrite 0.2%, orthoclase, zircon, in traces; the remainder is a fine-grained groundmass consisting largely of sericite and some carbonate.

(2) Slide No. CO. 25—Locality S21S10E. This strongly sheared rock consists essentially of quartz and feldspar grains of average size 0.2–0.3 mm in a fine-grained matrix of granular quartz and considerable fibrous sericite, arranged in wavy, sigmoid curves. Several of the quartz grains exhibit granulation around their edges, and one or two show finger-like processes following the pattern of the sheared groundmass. These fingers are optically continuous with the grain at their origin but become indistinct farther away. This appears to represent an early stage in the mobilization of the quartz. This rock consists of about 85% fine groundmass, chiefly granular quartz and sericite, about 14% quartz grains, and 1% plagioclase.

In hand specimen, this rock consists of a dark-gray medium to coarse impure sandstone, weathering to a rusty brown. In many places the rock contains flat shale fragments and characteristically shows spotty reaction to dilute HCl. Locally it shows signs of shearing and strong development of sericite.

Trenton black shales.—This lithological unit is the most extensively developed in the area and is variable in character. It is typically a very fine-grained black or brownish-black fissile shale which commonly exhibits strong cleavage, so that it is referred to as a shale or a slate. It has rarely developed sufficiently strong cleavage to be a good slate but is phyllitic in many outcrops.

Color banding and the presence of silty layers and limestone lenses in many places permit the recognition of bedding. In many places the bedding and cleavage coincide, suggesting that the cleavage is a bedding-plane parting. In others, however, axial-plane cleavage is excellently developed, as at Ancram (S22S20E). But in most outcrops, especially the smaller ones, only one well-developed direction of parting is seen, and it is difficult or impossible to decide whether it is true axial-plane cleavage or bedding-plane parting.

Limestone lenses 2–3 inches thick are believed to be near the bottom of the formation.

In many areas the shale is strongly crumpled into small folds ranging in amplitude from 2–3 inches to 1–2 feet. Where thin silty layers are present some crests of small folds seem to have been squeezed off and appear as small detached folds, as at (C31S9E) on the west side of the road on Mr. Harry Post's farm. Quartz veins are common, some about 6–8 feet thick, and are traceable for several yards. Most are parallel to bedding where this can be ascertained, though a few small veins are crosscutting. The quartz

is believed to be derived from the sandy layers in the shale. Much pyrite is present. In the more easterly part these pyrite crystals have been drawn out into elongate blebs along cleavage planes and partly or wholly oxydized to limonite; many bear a strong resemblance to graptolites.

The sandy layers commonly contain extensive patches of iron oxide and quartz, the appearance of which suggests the presence of organisms; very few fossils have been found, however. Two localities have yielded fossils, which are poorly preserved and deformed but are very common where they do occur. One locality is east of the Elizaville shale belt and one west. They are preserved as limonitic sandy casts and seem to be concentrated in the sandy layers. It is believed that they originated as pyritized fossils and subsequently oxidized to limonite, and that the limonitic patches mentioned probably do have an organic origin. Most of the fossils are brachiopods of the *Sowerbyella, Dalmanella* type and echinoderm ossicles. They suggest a Trenton age for the formation.

There are two main belts of black shale separated by a belt of Elizaville gray shale. The outcrop pattern shows that the black shale lies unconformably above the rocks of the carbonate sequence, in the east (a relationship noted by Fowler, 1950, p. 35, with respect to the Whipple marble-Hortonville slate in Vermont), and the structural interpretation adopted by the writer indicates unconformity above the Elizaville shale sequence.

Nevertheless there are anomalies in its relationship to the carbonate rocks. The Black River-Trenton limestone is also unconformable across the older carbonate rocks and east of Smith Hill grades up into the black shale. It therefore seems that the limestone is basal to the black shale in the region of the carbonate belt. However, several lens-shaped outcrops of black shale within the carbonate belt do not appear to have the limestone beneath them. These have been discussed above. There are probably slight local unconformities between the limestone and the black shale also. A further possibility is that there is an unconformity in the black shales themselves. If so, the likelihood of its being traced is remote.

In the relationship between the black shales and the gray Elizaville shales difficulty is again encountered. The western boundary of the Elizaville shale belt is sharply defined along most of its length by a line of westward overthrusting of the gray shales over the black. The same relationship can be traced southwestward into the Rhinebeck quadrangle (A. S. Warthin, Jr., personal communication). In a traverse across the strike, for example in the vicinity of Churchtown, typically developed gray Elizaville shales on the east pass abruptly into typical black shales; signs of overturning and overthrusting of the gray shales are apparent. The eastern margin of the gray shales is not so well defined; there is always an area of outcrops of a lithology intermediate between the black and the gray shales. At first it was interpreted as evidence for a downward transition from black shale into gray. Further work, however, has suggested that the black shale is unconformable above the gray-shale sequence. The gray-green quartzite and the calcareous grit are also considered part of the lower sequence. The black shale is considered of Trentonian age and may even extend upward into early Cincinnatian or Edenian. The anomalous relationship between it and the gray Elizaville shales is tentatively explained as a result of the fact that the encroaching black-shale sea would erode material from the rocks across which it advanced, and that in its basal part a certain amount of material from the underlying gray shale would be incorporated in its sediments and thus give them an intermediate character. Where the black shale overlies the carbonate belt it has argillaceous limestones at its base. The sharp western boundary is easily explained, since it is a faulted boundary, and lower horizons of the Elizaville shales are brought into direct contact with the black shale.

The thickness of this unit must again be estimated because of the usual difficulties of structure and cover. A little less than 500 feet, or much more, may be present.

Details of Exposures

It is a little difficult to select specific exposures, as the rock crops out in many localities and commonly has strongly glaciated surfaces.

(1) The exposure already mentioned, on the east side of Smith Hill at (SE30S3E), in a road cut,

is not an especially good outcrop of the black shale but is significant in that it displays well the gradational contact between it and the blue argillaceous limestone below. The shale is plunging eastward down the flank of the hill, in a series of small folds. The shale here is a typical black phyllite.

(2) The road cut east of Ancramsdale at (S46S-36E), also mentioned above, shows a small thickness of limestone below the shale and overlying Pine Plains dolomite. The relationships are complicated by faulting. Here the shale is distinctly phyllitic. The eastern contact between the limestone and the shale is a normal fault, and 20 feet above the fault is a layer of slightly dolomitic limestone 3–4 inches thick; there is a limestone layer 16 feet above the first.

(3) In the railroad cut at Hillsdale station at (NE51S30E) is a good exposure of black shale; here a small lenslike body of limestone is seen in the north bank just west of the road bridge across the tracks; a thin layer of limestone occurs 20 yards east of the bridge also on the north side of the tracks. In the same vicinity, in the pasture on the hillside immediately south of the road bridge, the shale crops out fairly extensively, and here good examples of thin sandy layers can be seen, with patches of limonite and quartz suggesting organic forms. Careful search has revealed no fossils. The pyritic streaks or blebs are also well developed in the exposures in the rail cut itself.

(4) At (NE47S33E) a roadside exposure shows a typical development of stronger slaty cleavage in the rock. Here again the elongate limonitic blebs are strongly developed. In this condition the rock takes on a silvery luster, probably because of the development of sericite along the cleavage planes.

(5) At (NE40S3E) some exposures in the fields on the northeast side of the crossroads show good development of thin cherty banding in the shale. The bands seem to be silty rather than true chert. These layers emphasize the finely crumpled nature of the structure which otherwise might not be visible; the rocks are thrown into small folds of amplitudes ranging from a few inches to 1–2 feet.

(6) At (C18S36E) in the little promontory on the south side of Lake Copake is one of the two fossiliferous localities in the area. Here the shale is typical black shale, shading to brown where weathered, and containing fine sandy layers with fossils in the form of molds and casts, strongly limonitic. The fossils are quite common here and consist mainly of echinoderm ossicles and some brachiopods. The latter are all deformed and are so poorly preserved that specific identification is impossible; they are, however, of "*Sowerbyella*" type.

(7) The other fossil locality is in the western black-shale belt at (W5S13E), where the shale crops out in some poorly exposed ledges in a pasture two fields west of the road. Here the fossils are preserved similarly; they consist mainly of brachiopods, equally poorly preserved. One or two fragments are *Dalmanella* (? *Resserella*), and one, in which the beak structures are fairly well preserved, is almost certainly *Dinorthis* (identification confirmed by G. M. Kay and G. A. Cooper).

(8) At (W3S6E) a road cut displays some very black, lustrous, phyllitic shale. It is strongly veined with quartz and contains pyrite nodules 1–2 inches in diameter. These have an irregular form which suggests organic origin.

(9) In a large road cut on Route 82 at (S22S20E), typical black shale is exposed; it is lustrous and contains pyrite blebs. This exposure is one of the few where bedding can be clearly seen, although there is little marked lithological variation perceptible on close examination. Banding, picked out on the weathered surfaces, is well developed. The exposure is also notable in being one of the very few where westward dips are observed. Good eastward-dipping axial-plane cleavage is developed here.

Limestone conglomerates.—Only two notable outcrops of limestone conglomerates have been found, as have two other poor exposures; all appear to be in the Elizaville shale series. Since these unusual rocks are not extensively developed in the quadrangle, discussion of them is limited here.

Details of Exposures

(1) The first outcrop is about 1½ miles north of Churchtown at (NW38S15E). The structure is synclinal, and the conglomerate occurs in its core. Here is exposed:

Top

(Feet)	
15–18	Blue-gray-weathering limestone with thin dolomitic sandy irregular partings with lenses of conglomerate; the fragments are of the rock itself.
5	Thin-bedded gray sandy dolomite weathering buff-gray, slightly cross-bedded in parts
5.8	Dolomitic sandstone, thin-bedded with faint suggestion of cross-bedding

Bottom

The limestone conglomerate here consists of fragments, all of the same blue-gray limestone in a sandy dolomitic matrix, and it passes laterally into the unfragmented limestone. It is clearly formed locally, probably penecontemporaneously, from the material *in situ*. The carbonate rocks are here underlain by about 20 feet of dark-gray shale, followed downward by a layer of calcareous grit.

(2) In the western outskirts of Claverack at (NW20S4E) limestone conglomerate crops out in a small ridge on the west side of the road. About 30 feet is present and consists of coarse fragments 1–5 inches in diameter of varied limestones, dolomites, cherts, and sandstone fragments in a matrix of coarse calcareous sand. It underlies gray shale of the Elizaville shale type. In the bank of the creek on the east side of the road, a fine grained, 10-foot, dark-gray dolomite, weathering rusty brown, is exposed. The structure is not clear. The conglomerate and shale in the western outcrop are dipping

steeply eastward. The dolomite in the bank of the creek, on the east side of the road and 132 feet away, is dipping steeply westward and is again dipping eastward in the bed of the creek about 15 feet to the east. There must be a slight synclinal flexure between the outcrops, but it renders the exact stratigraphic relationship between the conglomerate and the other rocks doubtful. The dolomite underlies the conglomerate, and the latter is clearly part of the gray-shale sequence.

The two conglomerates are distinct; one is composed of a variety of extraneous, mainly carbonate material, whereas the other is composed of fragments of the same limestone, clearly brecciated in place.

Two further outcrops of the former type are found at (NW16S32E) and at (NW1S39E). In neither case are they well exposed, and their stratigraphic relationships are obscure.

The Claverack outcrop is isolated in a wide area of alluvium, but the typical development of gray shale associated with it indicates that it is part of the Elizaville shale sequence. The outcrop north of Churchtown is also considered part of the Elizaville sequence, brought up in a small folded anticlinorium.

Berkshire Schist

This rock forms the mass of the Berkshire Hills where they extend into the quadrangle about 1½ miles along its eastern border.

Within the belt in which it crops out in the Copake quadrangle it is fairly uniform and consists of a hard quartz-chlorite schist showing fairly well-developed foliation which appears to be parallel to bedding planes. Magnetite crystals up to about 2 mm occur in small patches or layers.

The rock crops out extensively all over the mountains and can be studied easily in the Taconic State Park east and north of Copake Falls (Copake Ironworks on the map), on Washburn Mountain, and on Alander Mountain. These hills are thickly wooded and steep-sided, but one or two trails render access reasonably easy.

At the foot of the Berkshire Hills, where the cover of Quaternary deposits is absent, recrystallized limestones and dolomites are found. Consistently the limestone underlying the schist is a bluish-white recrystallized limestone, in places banded with white dolomitic layers and containing layers so similar to the fossiliferous layers of the Black River-Trenton limestone that it appears to be its metamorphosed equivalent.

This in itself provides very strong evidence for correlating the schist with the Trenton black shale. In addition the general appearance of the rock is closely similar to the black shale in spite of its metamorphism; and no sharp break is discernible eastward, especially in the Fox Hill area, in the southeastern part of the quadrangle. In this hill the shale passes from its unmetamorphosed state on the west flank of the hill, through a strongly phyllitic stage on the upper slopes, into a schist almost identical with that found just across the valley to the east in the Berkshires. A few miles south of this point Dana (1879, p. 385) observed similar phenomena, in the neighborhood of Amenia, and the two extreme rocks appear to be of the same age. Balk (1936, p. 767) summarized the arguments for correlating the schist with the unmetamorphosed shales in Dutchess County. There is also good supporting evidence for regarding them as correlatives in their consistent relationship to the limestone. This relationship is also found in the more highly metamorphosed parts farther east (Gates and Bradley, 1952, p. 15).

In view of the work being carried out elsewhere the term Berkshire schist is becoming little more than a terrane term, since the rocks are being subdivided into units reaching from Precambrian to Ordovician, but until such work is further advanced the term will suffice for this area. Because of its relationship to the limestone at its base the Berkshire schist in the Copake quadrangle is regarded as of Trentonian age.

Relation of Carbonate-shale Sequences

Stratigraphic relationships of the carbonate sequence, the shale sequence, and the Berkshire schist are largely inferred. So far, the best-established sequence has been worked out in the carbonate rocks, among which Knopf (1927; 1946) set up a stratigraphic scheme in the Millbrook quadrangle immediately south of the Copake quadrangle. Before her work these rocks had been referred to as Wappinger limestone, a terrane term for all the limestone in the Hudson Valley, although the presence of limestones of various ages had been recognized by Dwight (1879; 1888), Walcott (1888), and others. Balk (1936) was unable to map stratigraphic units in the carbonates farther south in Dutchess County. So far

Knopf has published only a reconnaissance account of these rocks made before her stratigraphic nomenclature (as found in a brief abstract) was set up; no map has yet appeared.

While no rocks below the Upper Cambrian Pine Plains formation are found in the Copake quadrangle, Knopf (1946), in the Stissing Mountain area of the Millbrook quadrangle, found the Middle Cambrian missing (though no structural unconformity is observed between the Lower and Upper Cambrian) and the Lower Cambrian represented by the Stissing dolomite underlain by the Poughquag quartzite. *Olenellus* fragments in the latter are reported by Knopf (1946, p. 1212).

For the rocks of the shale belt, establishment of a succession within these rocks and of a stratigraphic relationship between them and the carbonate rocks is required.

The broad regional structure of the shale belt is an anticlinorium, with axis striking north-northeast and located centrally in the belt of Elizaville shales.

The strong unconformity beneath the Trenton black shales and the repeated reverse faulting giving rise to an imbricate structure imply that the Elizaville shale sequence is older than the Trenton black shales. Ruedemann's (1942) map of the Catskill quadrangle, immediately west of the Copake quadrangle, shows that what is here mapped as Elizaville shale is continuous with his Lower Cambrian Nassau beds.

The Nassau beds were first named by Ruedemann (1914, p. 70) when he assigned names to the lettered divisions of the Lower Cambrian previously established by Dale (1904, p. 29) for Rensselaer County and part of Columbia County.

In the Catskill area, Ruedemann was able to map only Nassau beds (Dale's division A-E) and Schodack beds (F-J). He was unable to separate the Bomoseen grit, Diamond rock quartzite, and Troy shale, and they may be absent. Although most of the section is based on lithologic variations alone, other than *Oldhamia*, the Schodack limestones contain *Olenellus* and other Lower Cambrian fossils. Dale (1904, p. 31) also described several other localities in which graptolites were found (*Dictyonema* and *Clonograptus*), which were at that time ascribed to the Beekmantown. Ruedemann (1903, p. 11; Cushing and Ruedemann, 1914, p. 74) found similar and related forms at Schaghticoke, New York, and named the formation Schaghticoke shale, which he regards as basal Ordovician. The rock is described as a fine-bedded, black and dull-greenish to olive, siliceous and argillaceous slate with intercalations of thin gray and white limestone beds. In describing a similar outcrop near Schuylerville, containing the Schaghticoke fauna, he states that the rock consists:

> ". . . for the most part of light greenish gray, glazed argillaceous shale weathering to a light drab, with intercalations of coarser, more or less sandy mud shale and small streaks of black shale containing graptolites. It also contains three and one half feet of coarse grit with black calcareous and argillaceous pebbles and large, scattered rounded sand grains. One part of the formation is characterized by a number of calcareous sandstone beds, one-eighth foot to one foot thick which weather into characteristic chestnut brown sandy crust". (Cushing and Ruedemann, 1914, p. 73.)

The lithology described at the latter locality is similar to that of the Elizaville shales.

The lithological character of the shales in the Schaghticoke and those in the Nassau is very similar, and Dale (1904, p. 31) states that they resemble one another outwardly. Ruedemann (1903, p. 936) in his original description of the Schaghticoke shale states that ". . . it is evident there was no difference or break whatever in the physical conditions from the time of the deposition of the Cambrian beds to that of the Lower Siluric". Since he considers the Middle Cambrian missing in the Catskill area, it is a little difficult to visualize "no break in the physical conditions".

In beds mapped as Schodack in the eastern part of the Catskill quadrangle, southeast of Cherry Hill, graptolites indicating lower Deepkill age have recently been found in black shale interbedded with ribbon limestone and limestone conglomerates, and *Dictyonema*-bearing beds occur close by, though they may be separated by a fault. The forms found were *Triograptus* and an unidentified dendroid (Goldring, personal communication).

Since the limestone conglomerate at Claverack is roughly in the line of strike of the Cherry Hill section, it is almost certainly of the same—*i.e.*, Deepkill—age. Many of the rocks mapped

on the Catskill sheet as Nassau and Schodack are probably of Early Canadian or Late Cambrian age.

The Nassau beds of the eastern part of the Catskill quadrangle consist chiefly of grayish shales with thin quartzite bands, whereas in their typical exposure at Nutten Hook they consist of great thicknesses of quartzite (Goldring, 1943, p. 58).

The gray-shale series apparently ranges from Upper Cambrian into Deepkill. This is supported to a slight extent by the problematical graptolite found at Martindale. Only in view of the strong doubt concerning the age relations of the Nassau as mapped by Ruedemann in the Catskill quadrangle is this name abandoned in the Copake quadrangle and the name Elizaville shales, from the village in southeast Catskill, adopted temporarily. These shales may be younger than the black shales or older than any rocks in the quadrangle, but the available evidence favors the view adopted here.

The assumption of a Late Cambrian-Early Canadian age for the Elizaville shales raises the question of correlation with the units of the carbonate sequence, and also of the position of the gray-green quartzite and the calcareous grit.

If the age of the Elizaville shales as a whole is accepted as stated, then clearly the shales are equivalent to at least part of the Pine Plains and possibly some of the overlying limestones.

The gray-green quartzite in the lower part of the Elizaville shales is lithologically identical with the quartzite found in the Pine Plains at Ancramsdale. Similarly, the sandy dolomites in the Pine Plains, particularly in the exposures northeast of Tom Hill, bear a strong resemblance to the calcareous grit, especially where tabular shale fragments are found. The brown quartzite in the Pine Plains northeast of Ancram is not unlike some of the thinner bands of quartzite in the Elizaville shales.

The major part of the Elizaville shales may be time equivalents of the Upper Cambrian Pine Plains. However, it is not clear how much higher they extend. Since the limestone conglomerate at Claverack seems the same age as the similar rocks at Cherry Hill which contain Deepkill fossils—*i.e.*, lower Canadian—then evidently the Elizaville shales range up at least into the lower Canadian—provided it is accepted that the Deepkill shales are of that age. It is impossible to determine whether any parts of the Elizaville shales would be equivalent to the Briarcliff and Halcyon Lake groups. Some thickness of the gray shales may be their time equivalents, or their equivalents may have been cut out in the shale belt, just as they themselves have been cut out in this quadrangle. A considerable reduction in thickness from the carbonates to the equivalent shales is quite acceptable.

The broader relations of the overlying predominantly black shales are also uncertain. They could be equivalent to part of the Normanskill shales or of the Snake Hill shales or of both.

Ruedemann (1942a, p. 180) considers that the Normanskill shales are of Chazy-Black River age and pass up into the Snake Hill shales of Trenton age. The Snake Hill is separated from the Normanskill shales on paleontological evidence; the former contains a brachiopod-pelecypod-trilobite fauna, the latter a graptolite fauna. They may be facies equivalents of one another. The only fossils found in the Copake quadrangle are of the Snake Hill type, but this would leave no room for the Normanskill between the fossil locality south of Lake Copake and the Trenton limestone outcrop to the east. Since the fossils found in this limestone, which passes upward into the black shales, suggest a Black River-Trenton age, the black shale is also of Trenton age. Although graptolites could have been overlooked in the black shales, they are so abundant in other areas to the west and north it is unlikely that any extensive development of graptolite-bearing Normanskill shale has been overlooked. The Normanskill may be a facies equivalent of the Snake Hill (Trenton) type shales, or it may be stratigraphically distinct from and below these shales. In this case the Normanskill would be below the major unconformity. This alternative is accepted by most geologists and is favored by the writer. These stratigraphic correlations are summarized in Figure 5.

Structure

Regional Structure

The root zone of the shale series of the mass overthrust in the region was believed to be about 40 miles to the east (Keith, 1932; Prindle and Knopf, 1932, p. 297). The idea of thrusting on this scale was first postulated by Keith in connection with the discovery of Cambrian rocks among the shales in the northern Green Mountain region of Vermont and was strongly supported by Prindle and Knopf in their interpretation of the Taconic region. Ruedemann shows such an overthrust sheet on his maps. However, he refers not to one big overthrust, but to a large number of smaller thrusts giving rise to an imbricate structure (Cushing and Ruedemann, 1914, p. 106; Ruedemann, 1930, p. 137; 1942a, p. 139). His later idea concerning the deposition of the Cambro-Ordovician rocks in this general area does not take any widespread overthrusting into account, and it is doubtful if he conceived of the structure as involving movement of the extent postulated by Keith (Ruedemann, 1942b). Kay (1942, Fig. 1) also strongly supports the hypothesis of overthrusting and shows the klippe of the Taconic allochthone very much as it is delineated on the Tectonic map of the United States (Fig. 1). Cady (1945, Fig. 6) and Fowler (1950, p. 64, Pl. 11) show the Taconic thrust in western Vermont. In places overthrusting is apparent, as at Bald Mountain where Walcott found Cambrian fossils overlying Ordovician fossiliferous strata, and in western Vermont where strong westward thrusts are clear; evidence always appears on the western margin of the sheet; one of the major difficulties has been to find the rear or eastern edge of the klippe. No root zone has been found. In general the hypothesis of thrusting of the type suggested by Prindle and Knopf is based on the difficulty of interpreting the close juxtaposition of shales and limestones. The inference is that such rapid facies changes could not have occurred originally within the narrow confines of the Hudson Valley area and that the widely differing lithologies must therefore have been brought into juxtaposition by extensive overthrusting; the shales originated at least 40 miles to the east in Kay's Magog eugeosynclinal belt (Kay, 1951, p. 49, 66). However, it is difficult to believe that an overthrust of such extent could occur without leaving any well-marked structural evidence.

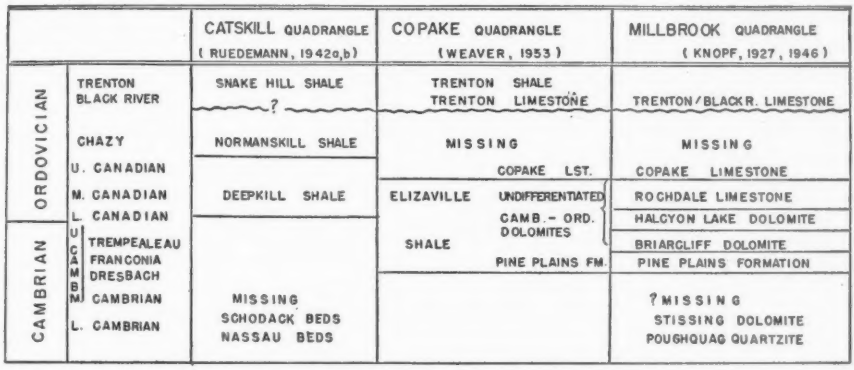

FIGURE 5.—PROPOSED CORRELATIONS

Probably the most significant outcrop in the quadrangle in reference to this problem is that in the road cut on the east side of Smith Hill (SE30S3E) where the black shale grades down into the blue argillaceous limestone of presumably Trenton age. This is the only exposure where the contact can be seen, though that in the road cut southeast of Lake Copake at (C20S43E) also shows no apparent break between the two rocks. The limestone is the

basal member of the black-shale sequence and as such rests unconformably across the older carbonate rocks, so that if there is a major overthrust it is not the black shales—in fact the thrust would have to be pre-Trenton. Since the relation of the limestone to the black shales and to the Berkshire schist and also to the phyllitic shales in Fox Hill is consistently uniform, obviously the Berkshire schist is not overthrust.

Similarly, the alternative that the black shale is itself part of the autochthonous sequence, with the edge of the allochthone farther to the west, is difficult to believe. There is no detectable break in the black shales westward, until the boundary of the gray Elizaville shales is reached. Here the relationship is not so well defined. Everywhere along the eastern boundary of the Elizaville shale belt outcrops are poor, and the exact boundary obscure. In most places irregular outcrops, first of black shale, then of gray, are found and attest to close infolding. The irregular relationship of the quartzite bands in the gray shale to the gray-shale–black-shale boundary and the distribution pattern of the gray-green quartzite and the calcareous grit all suggest an unconformity. This is to be expected, since a strong unconformity exists to the east under the Trenton shale-limestone series.

At the western boundary of the Elizaville shales the contact is quite sharp and, where best exposed near Churchtown, is clearly a faulted contact; the Elizaville shales are overturned and thrust over the black shale. This is well seen in the woods north of County Road 27, southeast of Churchtown at (W0S25E). The cleavage in the black shale west of the contact dips 60°–70°, in contrast to the cleavage dips of 30° or less in the Elizaville shales near by. Furthermore, small gently dipping thrust planes in the Elizaville shales are exposed along County Road 27; the best exposure is at (W10S31E). This sharp overthrust boundary of the gray Elizaville shales against the black continues southwestward out of the area and is mapped by Ruedemann (1942) in the Catskill quadrangle. Warthin has stated (Personal communication) that it is continued into the Rhinebeck quadrangle south of the Catskill.

If the Elizaville shales represented an overthrust klippe, the eastern boundary of the mass should show as sharp and well-defined an edge as the western. This is clearly not so.

The klippe hypothesis was formulated primarily because the presence of the dominantly argillaceous rocks in close juxtaposition to carbonate rocks of similar age was considered impossible in the same sedimentary basin. This conviction led Kay (1942, p. 1618) to say that the shales must have been deposited in the Magog geosyncline far to the east and carried west by overthrusting across the carbonate sequence. Even he, however, points to the fact that the typical volcanic rocks of the eugeosyncline are absent in the allochthone (Kay, 1951, p. 50).

Ruedemann (1942a, p. 141) points out the contrast between the strongly crumpled slates of the autochthone and the commonly undisturbed slates of the overthrust mass. Willis (1933) states that this is characteristic of overthrusts. This relationship is not observed in the Copake quadrangle. The degree of folding in both the Elizaville shales and the Trenton black shales varies. In both units, belts of very strong, small-scale crumpling are found. For example, in Green Hill, in the southwestern part of the quadrangle, the Elizaville shales are crumpled into folds 1 or 2 feet in amplitude, whereas westward across the strike about half a mile they are folded in gentle open folds about 6–10 feet in amplitude and about 25 feet in wave length. Similarly the black shales in several places (*e.g.*, at NE23S17E) are very strongly crumpled, whereas in other places they are not distorted, or the wrinkles are only 1–2 inches in amplitude. It is not easy to determine the structure in the black shale where the folding is very gentle. Strong crumpling is very evident where present, so that the black shale, too, displays a wide range of degree of deformation by folding. No distinction can be drawn between the degree of folding in the two units to support the hypothesis of an overthrust relationship as suggested by Ruedemann.

Furthermore, if the Elizaville shales represented a klippe there should be a similar sequence of beds on all sides. Such a repetition is not found. For example, the horizon which contains fairly closely spaced quartzite bands is fairly easily recognized. This occurs close to the eastern boundary of the Elizaville shales at

(N43S13E), but it is not found near the boundary farther south or north.

It is not known where in this area the boundaries of the hypothetical klippe are to be placed. That it cannot be the actual boundary between the carbonates and shales is clearly shown by the transitional contact between them. It has now been demonstrated that there is no ground for contending that the Elizaville shales form the klippe. The only place left to draw the boundary would be in the middle of the black shales. Its exact position would be impossible to place, since there is no marked break anywhere within these shales.

In the Copake quadrangle, then, there seems to be no evidence to support the hypothesis of long-distance overthrusting. Plate 1 presents an alternative that agrees with Ruedemann's (1914, p. 106; 1930, p. 141; 1942a, p. 138) concept that the Schuylerville, Capital District, and Catskill areas consist of many small overthrusts forming an imbricate or Schuppenstruktur. The carbonate rocks, too, are involved in this imbricate structure. Recent excavations for the widening of Route 22 in the vicinity of Copake support earlier interpretations and show Pine Plains rocks faulted against Copake limestone. The mass of Pine Plains rocks extending northeastward from Ancram to near Robinsons Pond has been displaced at least 2 miles westward by reversed faulting. Overthrusting of the Pine Plains over the black shales is also in evidence at the old Ancram Lead Mines at (S46S38E) where the spoil heap from the disused shaft, now water-filled, shows that black shale was reached below the surface, although Pine Plains dolomite is now exposed at the surface.

A few hundred yards northwest of this point at (S46S36E), in a road cut on Route 82, the blue Trenton limestone is exposed faulted against black shale. In the creek bed south of and below the road, Pine Plains dolomites are found with a thin fragment of the blue limestone in such a position that it can be interpreted only as being caught between two faulted blocks of Pine Plains dolomite. Figure 6a is a geological sketch map of the area, (scale 1:360), and Figure 6b indicates the structural interpretation.

A small quarry in the blue Trenton limestone at (E2S39E) shows strong drag folding and boudinage structures indicating overriding toward the west, and the Pine Plains rocks which crop out immediately to the north and east must have been overthrust.

Evidence of small overthrusts in the shale belt appears in the good exposures of the Elizaville shales along County Road 27 near Churchtown, where an actual fault can be seen. Although these structures are rarely directly observable in the field, enough are seen to suggest that the major structure is one of many small reverse faults.

The dominant and more obvious structural feature is that of small-scale foldings; widespread folding ranges from small flexures 2–3 inches in wave length and in amplitude to folds 30–40 feet in wave length and 10–15 feet in amplitude. Almost every fold is overturned westward, though the degree of overturning varies from a slight asymmetry to near horizontality of both limbs. Dana (1887, p. 399) likened the structures to the crumpling of the cloth in the crook of the elbow.

The plunge of the minor fold axes shows no distinct pattern; in some places axes plunge in opposite directions in the same outcrop. Balk (1936, p. 701) stressed the fact that all folding is minor. The importance of small-scale maps indicating the plunge of minor fold axes should not be overestimated. For example at (C334S11E) the minor fold axes plunge in one place toward N. 23° E., whereas 200 feet away they plunge S. 26° W. These small-scale folds normally hinder interpretation of the relationship of the rocks from one outcrop to the next. On the whole it seems that the shales have yielded to deformation by small-scale folding, whereas the more competent grits and quartzites have yielded by reverse faulting unless the deforming forces were mild, in which case gentle folds have been formed in them. For example at the Pinnacle the gray-green quartzite in places has been thrown into small gentle folds, though faulting has also occurred.

Areas of very strong crumpling are localized; probably no single external deforming force could be transmitted in such an irregular manner. A clue to the probable nature of the forces immediately responsible for the deformation is suggested by the anticline that extends from Chrysler Pond north-northeast toward Lake Copake and brings the Trenton limestone up

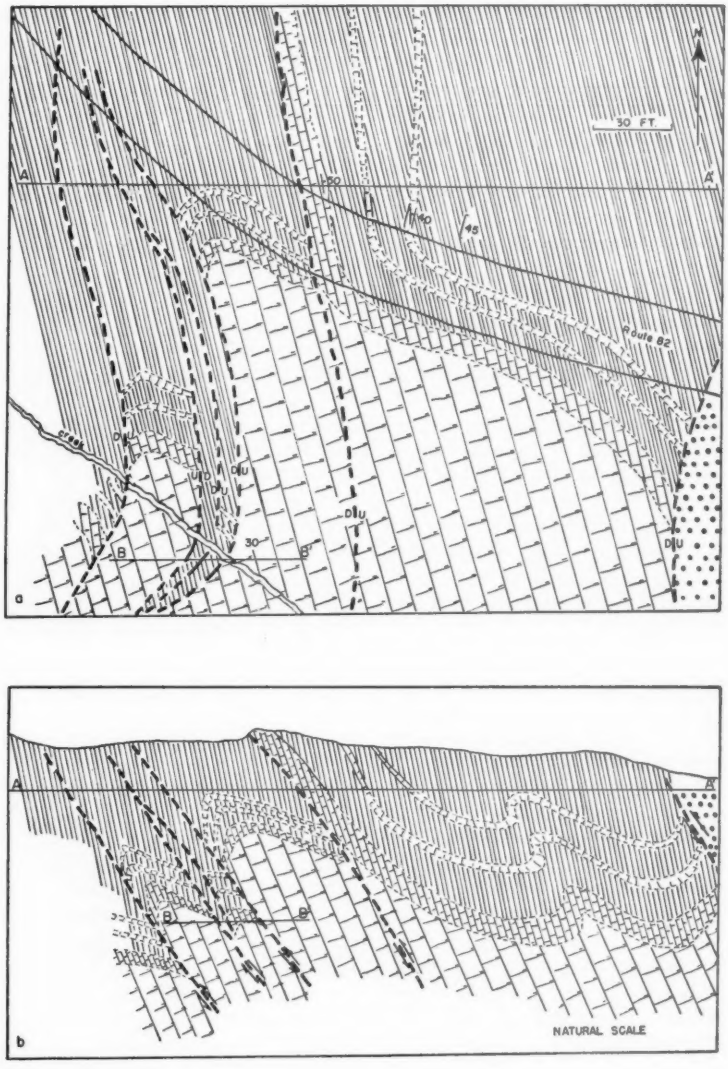

FIGURE 6.—GEOLOGICAL SKETCH MAP OF SMALL AREA AT S46S36E NEAR ANCRAMSDALE, WITH CROSS SECTION (B)

The section along the line B-B′ has been projected into the plane of A-A′.

through the black shale. This structure is located along the front of the thrust block of Pine Plains rocks, which crop out farther east. Very possibly it just coincides with the line of the inferred fault. Since the Trenton shales and limestone lie unconformably above the older rocks it seems reasonable that the fold in the limestone and shales was caused by movement on the fault in the underlying rocks. This would provide a general explanation for the irregular distribution of the areas of intense folding. From the Chrysler Pond anticline and the over-all outcrop pattern it would appear that the block of Pine Plains rocks had been shifted westward at least 2 or 3 miles. If this is so, most of the movement on the fault must have taken place before the Trenton rocks were laid down; otherwise considerably more than a 15-foot anticline would have been formed in them. The fault then was already in existence before the Trenton transgression, and slight movement took place along it subsequent to the deposition of these rocks. A comparable though more complex example is that at Ancramsdale. This implies that the immediate cause of the deformation of the shales was shortening of the basement. (*Cf.* Lees, 1952.) This relationship may be of more than local significance in this part of the Appalachian foreland.

As a whole the general trend is roughly N. 35° E., and the regional structure is a series of complex synclines and anticlines.

The axis of the more westerly anticlinorium passes through the western shore of Lake Taghkanic (Lake Charlotte) and the Pinnacle. To the east of this is a synclinorium of Trenton shale, through which a few areas of the older Elizaville shales with the calcareous grit show in minor anticlinoria. This again is followed eastward by the main area of carbonate rocks which is anticlinorial in that the rocks are all older than the shale and schist on either side, though the anticlinal pattern is partly produced by the exposure of the carbonate rocks in a lower-lying valley.

The interpretation that the Elizaville shales form anticlinal areas is based to some extent on the fact that they are correlated with the Pine Plains formation and would thus be older than the Trenton shale. Nowhere have the gray Elizaville shales been found over the black Trenton shales, but at one point east of Green Hill and at several points northwest of Ancram they underlie them. At (C41S2OE) the Elizaville shale and the calcareous grit are found in an anticline plunging southwestward below the black shale. Immediately east of Lake Taghkanic a wedge of black shale extends northward into the Elizaville shales. The fact that the minor folds here all tend to plunge south-southwestward indicates synclinal structure (Fig. 7).

Warthin (Personal communication) suggested that the gray shales are a band within the black shale and that the areal structure consists of the inverted upper limb of a huge overturned syncline; the rocks, therefore, become progressively younger toward the west. This does not seem to fit the structural facts available. It does not take into account the fact that Deepkill beds are found just west of the quadrangle, which would involve an almost complete cutting out of the whole thickness of beds, which according to this hypothesis extend across most of the Copake quadrangle.

The gray shale may be entirely younger than the black, in which case the area interpreted here as an anticlinorium would be a synclinorium. However, the anticlinorial interpretation is preferred.

The broad trend of the outcrop pattern, which is north-northeasterly and parallels the line of small Silurian-Devonian outliers at Becraft Mountain and Mount Ida, suggests post-Devonian warping. This trend is at variance with that of the structures both in the Elizaville shale and carbonate belts, which is very much closer to north-south.

Cleavage

Cleavage is the most prominent minor structural feature in the rocks of this area. It is, of course, most conspicuously developed in the shales but is also strongly developed in the Trenton limestone; an irregular cleavage can be perceived in many of the dolomites and seems to be responsible for the characteristic hackly, rugged appearance of weathered surfaces, particularly among the Pine Plains dolomites.

In many outcrops of the shales only one

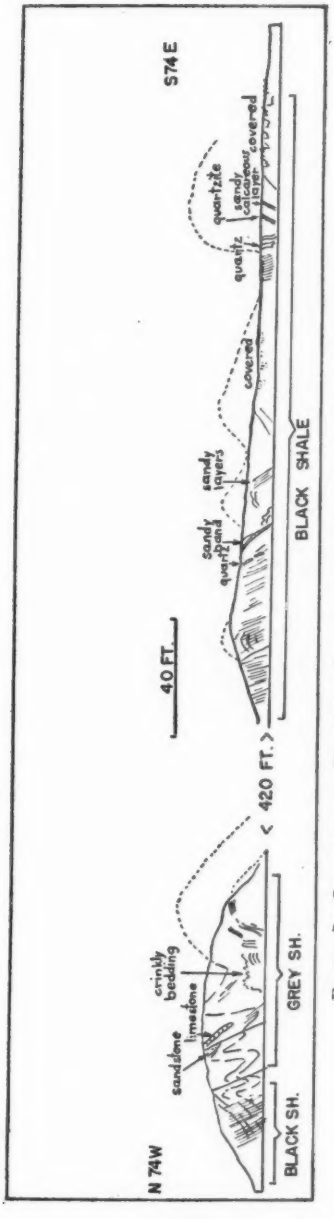

FIGURE 7.—SECTION ALONG EAST-WEST ROAD IN LAKE TAGHKANIC STATE PARK AT (W51S27E)

planar direction can be seen, and in most places it is impossible to determine whether this direction is a cleavage direction or original bedding. Where close examination reveals a slight lithological variation that indicates the direction of bedding, the variation is parallel to the more evident direction of parting and indicates that the cleavage direction is generally parallel to bedding. In places, however, the cleavage cuts across bedding planes, as in the road cut at Ancram at (S22S20E) where the bedding dips westward and the cleavage eastward.

Where the larger folds can be easily seen,—for example, farther south on the ridge in which the last-mentioned exposure occurs, and in the well-exposed anticline in Trenton limestone at Chrysler Pond—the cleavage bears an axial-plane relationship to the folds. Inasmuch as the folds are all asymmetrical toward the west, the cleavage invariably dips eastward.

Casual examination of the area gives a strong impression of uniformity in strike and dip of the cleavage. Pepper (1934) measured cleavages over a wide area in the Hudson Valley and found that the cleavage strike is uniformly N. 10° E. In the Devonian beds near by the cleavage strike is N. 25°–30° E. which must be younger than the Taconic orogeny. He therefore infers that N. 10° E. is a Taconic direction and N. 25°–30° E. Appalachian. Plate 4 records cleavage readings well scattered over the Copake quadrangle in both Elizaville shales, Trenton shales, and the carbonates. Many of the readings are averages over a large outcrop.

The cleavage strike varies over a wide range, even within small areas, and it is unlikely that orogenies can be distinguished on this basis. In fact, the cleavage directions seem to be related to fold axes, and although these show a rough alignment there is considerable variation in detail.

Bent cleavage, reported from some neighboring areas, has not been observed in the Copake quadrangle except in several instances where it is clearly related to movement on a fault.

Metamorphism

Only low-grade metamorphism has modified the rocks in this quadrangle and that mainly in the eastern part; the Berkshire schist is a quartz-chlorite schist. Higher-grade metamorphism continues east of the quadrangle into Massachusetts. Since the Berkshire schist is regarded as Trenton in age, the metamorphism must be post-Trenton.

From west to east across the shale belt, the shales become slightly more phyllitic, though the increase is not regular. The phyllitization which seems to occur locally in the road cut at Ancramsdale, in the road cuts southeast of Lake Copake, and in the small road cut in Hillsdale may be associated with local deformation, either faulting or folding, rather than part of a regional metamorphic pattern. In scattered areas—*e.g.*, at Green Hill—the Elizaville shales are more phyllitic; this is clearly associated with local folding and probable faulting. Phyllite cannot be regarded as a regional metamorphic grade.

Veins of quartz up to 4–6 feet thick and traceable along the strike for 40–50 feet are common throughout the shale belt; most are in the black shales. They almost invariably parallel bedding planes, where the planes can be defined, though a few crosscutting veins have been observed. These veins probably originated from the sandy or cherty layers in the shales and were either formed in place or derived from near by. What appears to be an early stage in this process can be seen in thin sections of the sandy rocks, where quartz fragments have been recrystallized around their edges and have sent out "feathers" into the adjoining interstices. Several examples of this phenomenon show these radiating feathers arranged normally to the cubic faces of pyrite crystals.

No formation of metamorphic minerals has been observed in the recrystallized limestones, though the Trenton blue limestone, close to the Berkshire schist, commonly contains layers of scattered chlorite flakes, which were presumably derived from the argillaceous material in the original rock.

Geological History

In the Copake area the oldest rocks are of Late Cambrian age. The nearest Precambrian rocks are found at Stissing Mountain, 2–3 miles south of the Copake quadrangle. To the

northeast, Precambrian gneisses and schists are found in western Massachusetts and southern Vermont. The relationship of these Precambrian rocks to the overlying Lower Paleozoic rocks is not yet clarified, though they appear to be overlain unconformably by the basal quartzite of the Lower Cambrian—the Poughquag at Stissing and the Cheshire to the northeast.

Ruedemann (Cushing and Ruedemann, 1914, p. 114), following Ulrich (1910, p. 442), suggested that after the end of the Precambrian the whole region from the Adirondacks to the Green Mountains became divided by rising land barriers into three north-northeastward-trending troughs of deposition: the western, or Chazyan, trough, the middle, or Levis, trough, and an eastern trough. According to this hypothesis, deposition took place alternately in the troughs; thus, in the Early Cambrian no deposition took place in the Chazy trough while the Nassau and Schodack beds were deposited in the Levis trough and the Cheshire quartzite was deposited in the eastern trough. In the Middle Cambrian, no deposition appears to have occurred anywhere. In the Late Cambrian, the Potsdam sandstone was deposited in the Chazy trough and was followed by the Theresa and Little Falls dolomites and sandstones; at the same time the lower Beekmantown dolomites (Stockbridge limestone) were being deposited in the eastern trough, and the middle or Levis trough received no sediments.

Early Ordovician time, according to this hypothesis, opened with the deposition of the Schaghticoke, which was followed by the Deepkill shales in the Levis trough and continuation of limestone deposition (Beekmantown) in the eastern trough; no deposition occurred in the Chazy or western trough. By Black River-Trenton times deposition again proceeded in all these troughs and became shale deposition throughout by late Trenton time (Ruedemann, 1942a, p. 136, Fig. 50).

Ruedemann (1942b, p. 56, Fig. 9) soon abandoned this hypothesis and suggested that possibly there was only one trough of deposition; in it shale was deposited in abyssal depths in the central part, and littoral deposits accumulated in the east and west.

In neither interpretation is it clear to which sequence or trough the carbonates of the Harlem Valley belong.

In the areas neighboring the Copake quadrangle the Middle Cambrian appears to be absent. In the Lower Cambrian, it is significant that the lowest rocks, the Nassau, are not directly dated. The only fossil found in them is *Oldhamia*. The overlying Schodack beds contain lower Cambrian fossils in many localities (Ruedemann, 1930, p. 80, 81), and it was presumably on the basis of its relationship to the Schodack that the Nassau was interpreted as Lower Cambrian. Lithological correlations with the Schodack, probably based on the prominent limestone conglomerates, have been shown to be in error in the eastern and central parts of the Catskill quadrangle, and possibly the correlation of the beds mapped as Nassau in these areas was also in error. A detailed restudy of the rocks hitherto classified as Lower Cambrian is necessary.

In the Cambrian a shore line extended in the west along the flank of the Adirondacks. By Late Cambrian times algal reefs were flourishing (Goldring, 1938), and similar reefs are found in the Pine Plains dolomites around Stissing Mountain and in the Copake area. Rocky islets of Precambrian rocks—*e.g.*, Stissing—probably stood above the Upper Cambrian shelf seas, fringed with algal reefs. The whole aspect of the Pine Plains formation is strongly indicative of reef conditions—dolomitic sandstones, oölites, algal dolomites, edgewise conglomerates, and some shales—and the major features of the region in Late Cambrian time were probably extensive barrier reefs extending north-northeastward, with a wide lagoon area to the west where clastics of the Elizaville shale series were deposited contemporaneously. In the Catskill quadrangle Ruedemann (1942a) did not find any rocks he considered of Late Cambrian age, so it is uncertain that shale was deposited in that area during this period. Ruedemann (1942b, Fig. 9) must have considered this possible, however, since he shows it in his reconstruction of the single depositional trough. Probably some, at least, of what he considered to be Early Cambrian may well be Late Cambrian.

A facies variation similar to this probably existed in the Upper Cambrian. The Pine Plains group is a very heterogeneous assortment of shales, sandstone, and dolomites, with some predominance of the latter; the Elizaville shales

are very similar, though they lack thick dolomites. Allowing for an aggregate of 5–10 miles shortening caused by the imbricate nature of the faulting, such a change of facies within the distance available does not seem unreasonable. The fact that the gray-green quartzite in the Pine Plains and that in the Elizaville shales are identical, as are the calcareous grit in the Elizaville shales and the sandy dolomite in the Pine Plains, makes such a correlation reasonable. At the least, these lithological similarities indicate that the facies variation is not excessive.

Information available on the types of sedimentation taking place in inter-reef areas is limited. Fairbridge (1950, p. 374), in his discussion of the Great Barrier Reef of Australia, indicates that terrigeneous material is accumulated rapidly and extends over the entire shelf; it is distributed by strong currents in the barrier lagoon. He states that near the land terrigeneous material commonly exceeds 90 per cent, whereas in the vicinity of the reefs organogenic clastic materials and precipitated calcareous material form up to 98 per cent of the sediments. He points out that the proportion of massive reef rock to total sediment is very small:

> "... although the Reef shelf sediments are mainly terrigeneous, they include numerous irregular lenses of organogenic reef sands and limestones. *There is no solid mass of coralline material extending from the coast to the edge of the continental shelf.*" (Italics added by the present writer.)

Cloud (1952, p. 2138), in his discussion of facies relationships of organic reefs, states that the barrier reef should interfinger lagoonward, first into lime sands that surround the irregular patch reefs and eventually into lime sands that may or may not be interspersed with scattered patch reefs. "However," he says, "it may instead pass lagoonward to evaporites or purely clastic sediments." (*See also* Henson, 1950, Figs. 12, 13.)

Schuchert (1937, p. 1048) describes the Upper Cambrian Hungerford slate of Vermont as almost wholly blue-black to gray, well-banded slates, which contain many limestone bioherms and a few lentils of dolomite. These bioherms are described as having grown in a mud environment and being largely or wholly of algal growth. Although Bradley's (1925, p. 129, 130) description of the shore phases of the Green River formation of Wyoming, with associated algal reefs, deals with fresh-water lake deposits, it contains some surprising analogies in respect to the sediments associated with the algal reefs, which lend some support to the suggestion made here concerning the conditions of deposition.

The grits, with their ill-sorted angular grains and heterogeneous content, were probably deposits formed in association with downslope slumps or associated turbidity currents and do not necessarily imply periodic uplift of the sea bottom. The work of Ewing and associates (Ericson *et al.*, 1952) has shown that such coarse deposits can be formed in very deep water.

The late Late Cambrian and early Ordovician history is obscure in this area, since the rocks of this age in the carbonate belt have been largely concealed by thrusting and unconformity. Evidence from the area to the south suggests that more-stable conditions of limestone deposition set in and continued with occasional interruption through Briarcliff, Halcyon Lake, and Rochdale time—*i.e.*, late Late Cambrian and early Canadian (Knopf, 1946).

In the west, in the central part of the trough, conditions seem to have persisted without change from Late Cambrian into Early Ordovician. The arrival of graptolites in the deeper part of the trough is suggested by the doubtful *Hologroptus* found at Martindale, and farther west good Lower Ordovician graptolites are found in the Deepkill—*e.g.*, at the Cherry Hill locality, only a few miles west of the western border of the Copake quadrangle.

During this time occasional slumping appears to have taken place into the deeper parts of the trough, giving rise to the limestone conglomerates, which are well developed immediately to the west in the Catskill and Rhinebeck quadrangles. Some of the conglomerates appear to be caused by local and contemporaneous brecciation of the limy muds at the bottom, as, for example, that described in the vicinity of Churchtown. Possibly incipient folding and faulting had already occurred. Indeed, it is usually suggested that these slumps probably needed earth movement to trigger them off.

Late Canadian time is represented by the

Copake limestone, which contains about 100 feet of sandy dolomite at its base. The derivation of the detritus is not clear. It contains mainly quartz, with a little plagioclase and some microcline, which suggest a derivation from a metamorphic terrane; the direction of cross-bedding is not sufficiently well defined for any definite statement of the direction of transport, but a few observations in the quarry at Tom Hill suggest easterly transport. Fragments are angular and appear to have been derived first hand from some local landmass. It can merely be suggested that small islands were still above water in the neighborhood. Shallow conditions were probably prevalent in the eastern part of the area, with neighboring uplifts providing the sediment, giving way in Late Copake time to more stable conditions and clearer water, allowing the deposition of the purer dolomites and limestone.

Toward the close of the Canadian, earth movements which may well have been gently proceeding for some time became stronger, and compressive movements caused extensive overthrusting along numerous faults and finally emergence of the whole area.

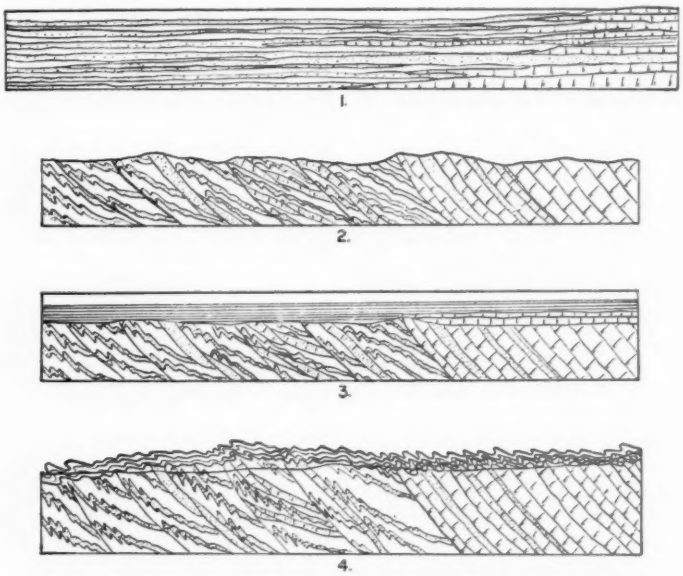

FIGURE 8.—STAGES IN THE INFERRED GEOLOGICAL HISTORY OF THE AREA

(1) Late Late Cambrian time; the sediments of the limestone banks around offshore islets (or possibly back-reef areas) are shown in the eastern part of the section, interfingering westward into the muddy basin facies sediments.

(2) Late Early Ordovician time; compressional movements have effected shortening by numerous reverse faults, bringing carbonate rocks into closer contact with argillaceous rocks.

(3) Late Trenton time, showing the transgression of shales across the whole area, with limestone deposited locally over the old carbonate area.

(4) Late Ordovician or early Silurian time; further movement on the faults has produced crumpling of all the sediments and in some places overthrusting of the earlier rocks over the Trenton shales. The present topography is indicated.

The Chazyan appears to be absent in this area, unless the blue crinoidal limestone here regarded as Black River-Trenton is Chazyan. This is not impossible although it is unlikely. The contained fossils are not diagnostic, but lithologically the limestone resembles more closely the known Black River-Trenton elsewhere.

Chazyan time may be represented by the Normanskill shales in the west or central part of the trough, although no possible correlative in the eastern part is known.

In early Black River-Trenton time a rapid flooding must have taken place, for the uncon-

formity below the overlying shale sequence is widespread but is not marked by any pronounced deposition of coarser material which would constitute a basal sandstone. Where the sea advanced across the shale area the deposits incorporated some of the material of the underlying rocks. In the vicinity of the carbonate belt the sediments were fairly pure lime mud with much fragmented organic material. Limestone deposition was restricted by the sea's advancing over a coastal-plain type of topography. The fault blocks probably formed ridges and troughs and thus contained the lime mud within the area underlain by carbonate rocks.

Finally, black-shale deposition became general. Brachiopods and echinoderms are the only organisms found in these shales in this area. The development of quantities of pyrite indicates reducing conditions and suggests that water circulation was inhibited, possibly by the division of the bottom into narrow troughs between fault blocks.

Soon after the deposition of these shales, movement along pre-existing faults caused folding and in places overriding by older rocks. The presence of limestone conglomerates containing Black River fossils (Ruedemann, 1942a, p. 120) in the Catskill quadrangle and the fact that the faults were active before the Trenton deposition indicate that the fault movements were intermittent throughout the whole time.

The final stage of the Paleozoic history of the area is not recorded in the Copake quadrangle. Immediately to the west in the northeastern part of the Catskill quadrangle, at Becraft Mountain, the relatively gently folded Manlius limestone lies with strong unconformity on the strongly folded Normanskill shales and thus places an upper time limit on the major deformation of the older rocks. It also indicates that the area must have been emergent for some time between the Middle Ordovician and the Late Silurian.

Whether the later Appalachian orogeny had any great effect in this area is not clear. From other areas evidence such as folded cleavage (Broughton, 1946, p. 18) has been brought forward to support the view that the rocks were strongly affected both by the Taconic orogeny and the Appalachian. In the Copake area most of the evidence points to a pre-Trenton date with undoubted further movements after the deposition of the Trenton, but whether soon or long after is not clear. The smaller amount of deformation affecting the Becraft Mountain outlier of Silurian and Devonian rocks suggests that the Appalachian deformation was not strong in this vicinity, although regional warping may have occurred. Orogenic activity in the northern Appalachians was perhaps not confined to definitely bounded comparatively short periods, such as the Taconian or Appalachian, but may have continued intermittently for a long time. (*Cf.* Gilluly, 1949.) The locus of intensity seems to have shifted in time.

After the Trentonian no direct evidence of the geological history is found until the Pleistocene. No special study has been made of the geomorphology or of the Pleistocene deposits of the area.

The geological history of the areas as interpreted here is summarized in Figure 8, which represents hypothetical cross sections across the area at various stages.

Summary and Conclusions

Mapping of the Copake quadrangle demonstrated that there is no evidence for the hypothesis that the argillaceous rocks of the Hudson River Series are part of a klippe, as suggested by Prindle and Knopf (1932).

The rocks include an eastern carbonate sequence and a western shale sequence. A large part of the carbonate rocks present in the quadrangle to the south (Millbrook quadrangle) is missing here; they are partly cut out by faulting and partly concealed under the unconformity.

Of the shale sequence, that part which is continuous with the outcrop previously mapped as Lower Cambrian Nassau beds in the quadrangle to the west (Catskill quadrangle) is here considered to be of Late Cambrian-Early Ordovician age; it is correlated with the Upper Cambrian Pine Plains formation of the carbonate sequence and possibly with the Lower Ordovician members of the carbonate sequence, some of which are cut out in this area. They have been named here the Elizaville shales.

A paleogeographical interpretation suggests that the carbonate sequence represents back-

reef deposits on the western side of a series of barrier reefs or reef-girt islands and grades westward into terrigeneous clastic sediments of the basin facies—shales, siltstones, and calcareous grits.

The Berkshire schist in the east is a more highly metamorphosed equivalent of the Trenton shales.

The regional structure consists of a widespread unconformity of Trenton shales across the Cambrian and earlier Ordovician rocks. The Trenton shales have a thin limestone at their base where they transgress the older carbonate area.

The rocks below the unconformity are broken into imbricate fault blocks; evidence shows that the major part of the reverse faulting was pre-Trenton or early Trenton and that subsequent movements on these faults caused at least some of the deformation of the transgressing Trenton shales. In some places the older rocks have been overthrust onto the Trenton shales. Some evidence suggests that some of the folding may have preceded lithification.

Cleavage, although showing a rough alignment, varies widely, and an earlier orogeny could probably not be distinguished from a later one by a study of the cleavage directions. These seem to be more closely related to fold axes which show some rough parallelism.

Some post-Silurian warping may have affected the area and given rise to the broad northeast-southwest trend of the broader anticlinorial and synclinorial areas.

Since there is only a small area of metamorphic rocks in the quadrangle, the problem of metamorphism has not been studied. It is hoped that this study of the unmetamorphosed rocks will assist in the elucidation of the problems of the highly metamorphosed rocks to the east—a remarkably good region in which to investigate metamorphic phenomena.

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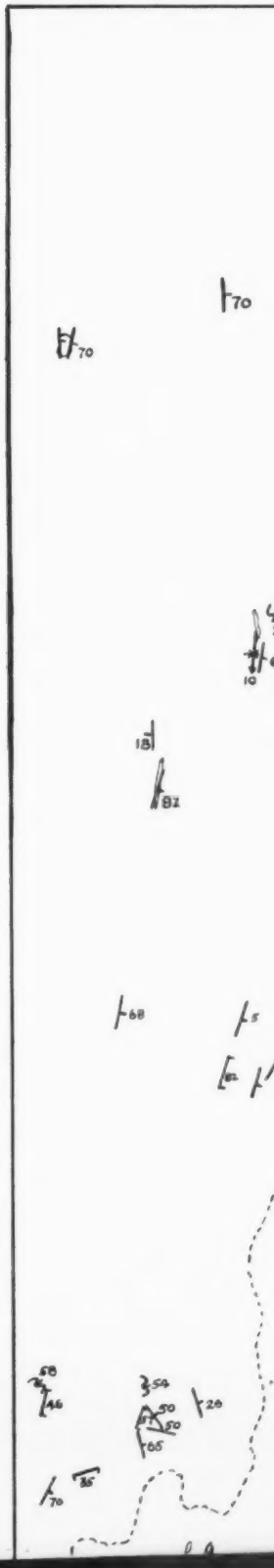
Manuscript Received by the Secretary of the Society, June 22, 1954



LEGEND

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PLUNGE OF MINOR GRENULATIONS

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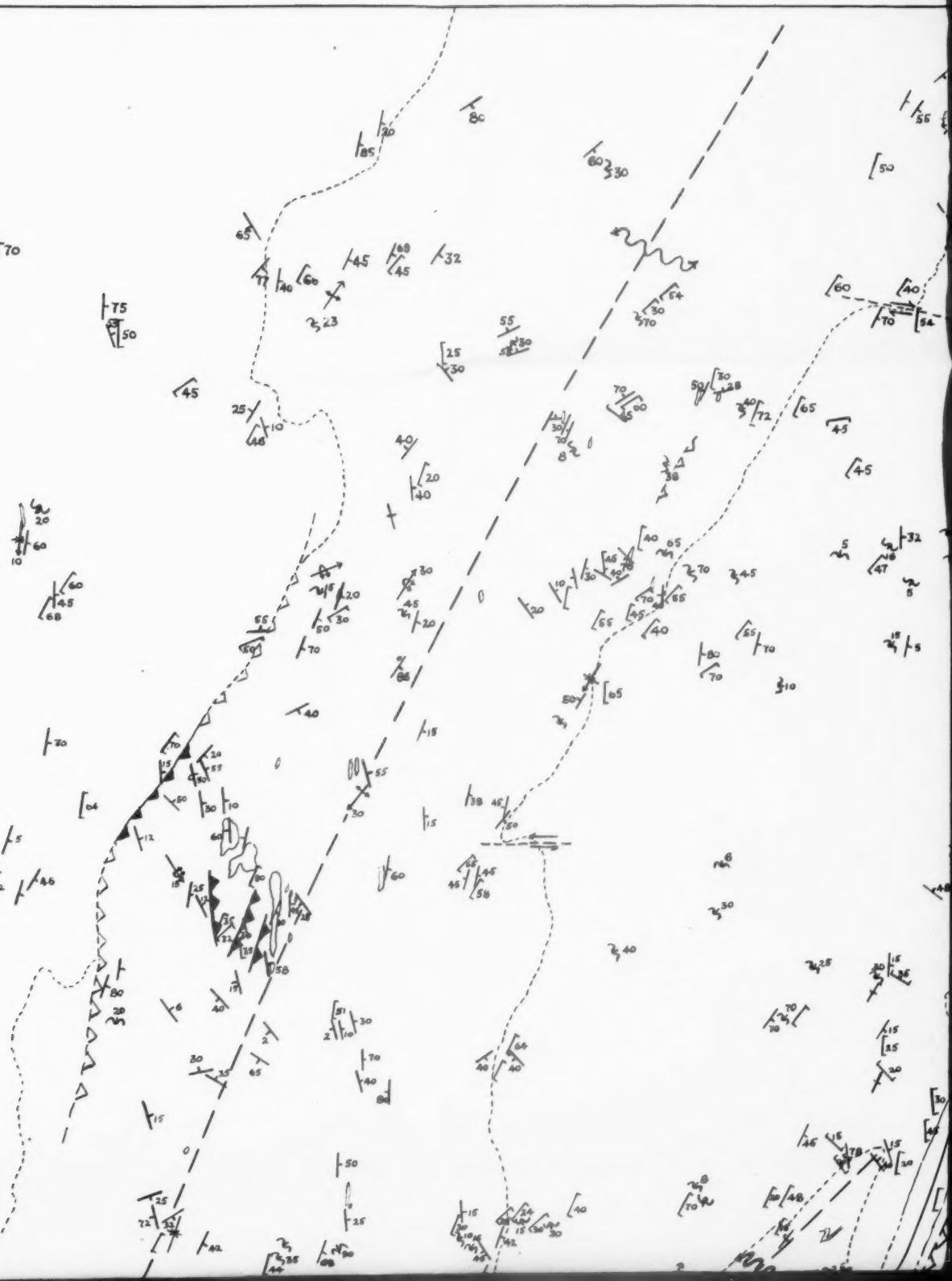

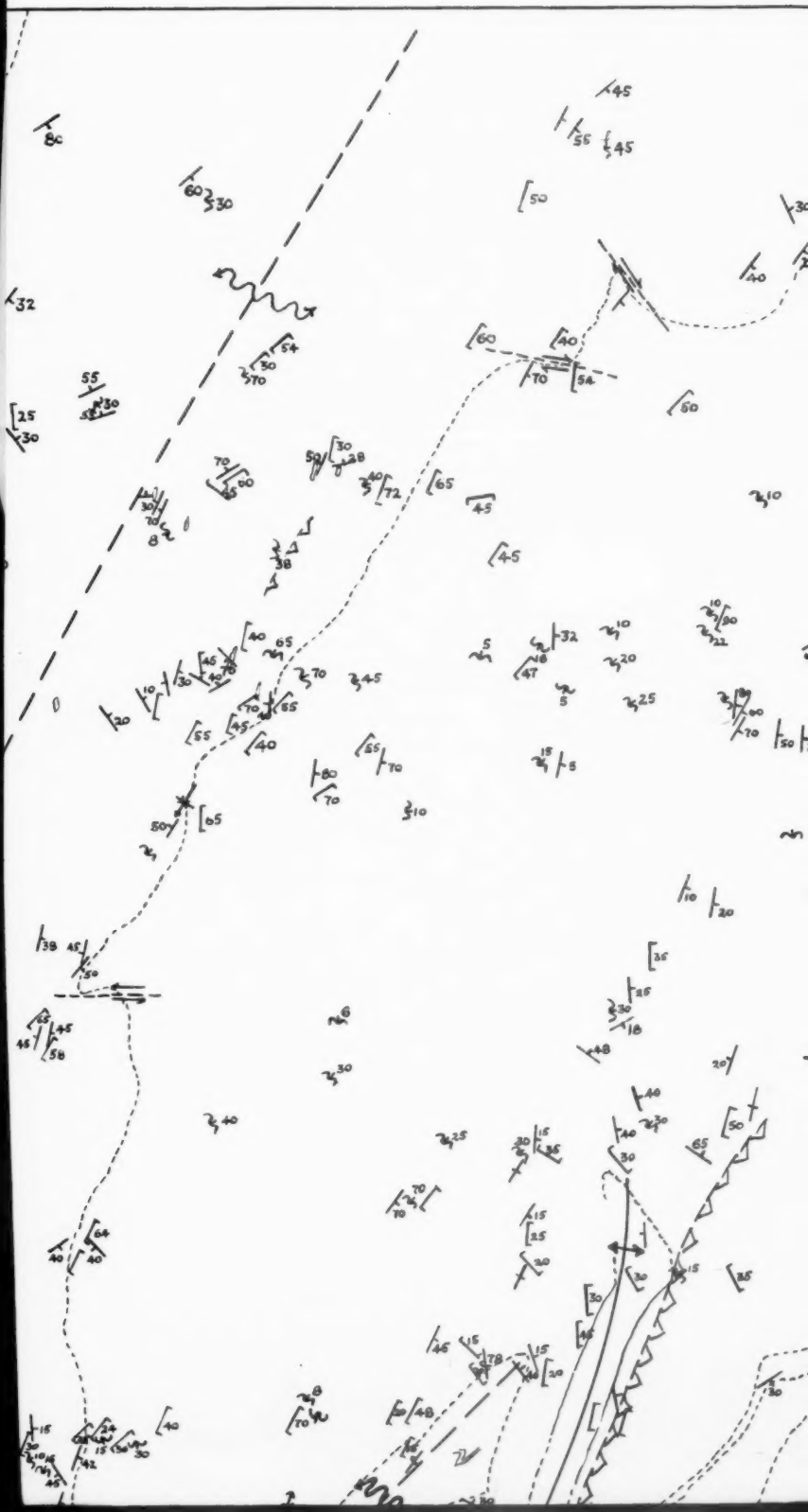

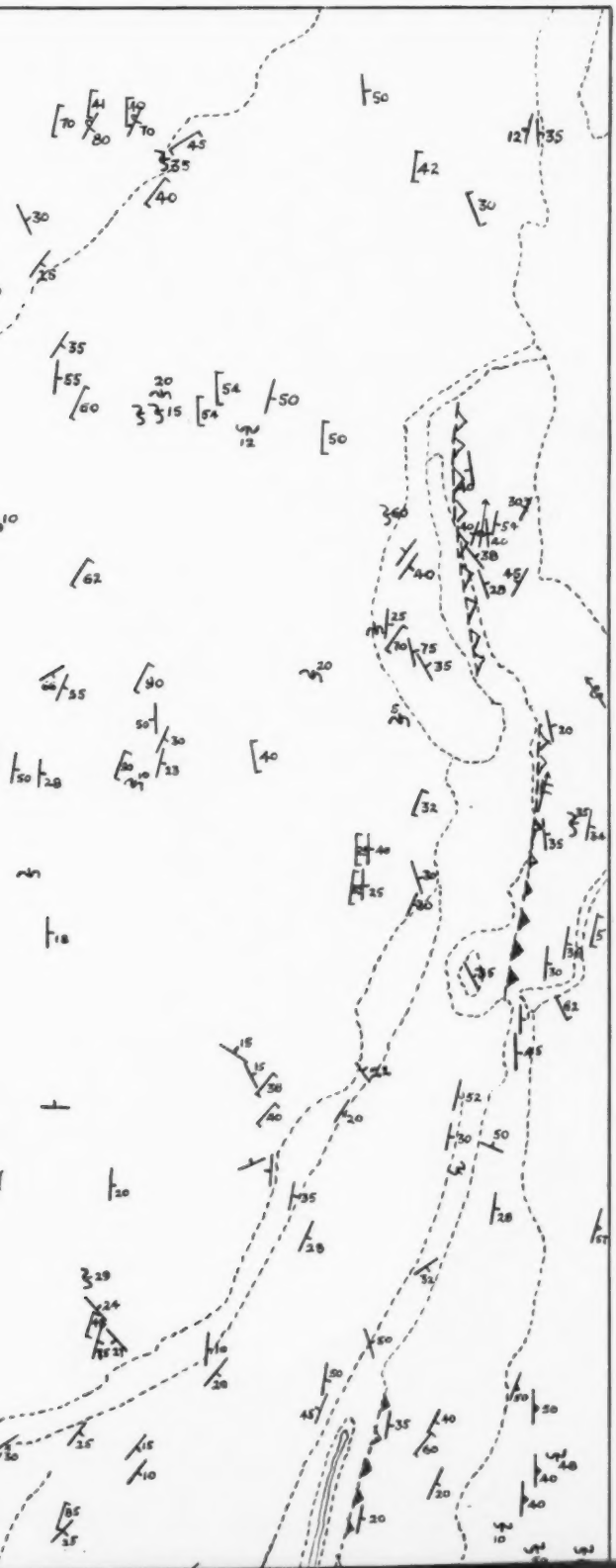

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APPROXIMATE AXIS OF ANTICLINORIUM

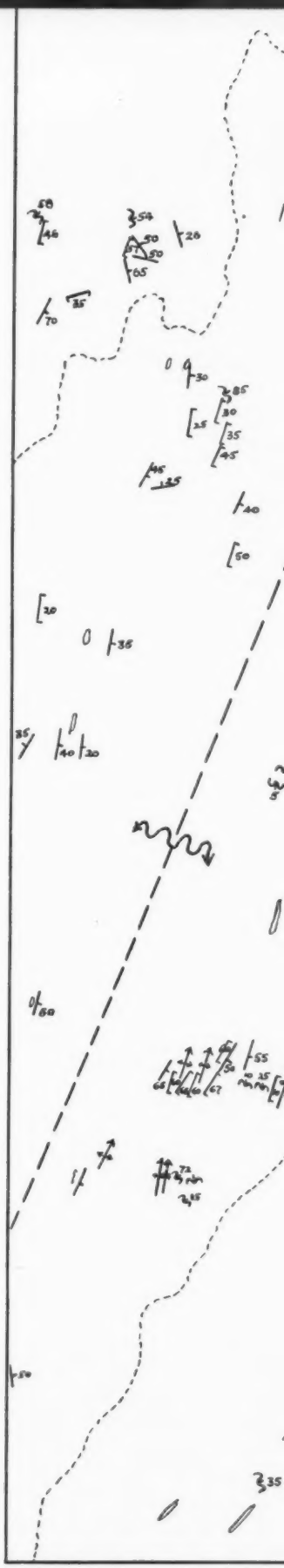
FORMATION BOUNDARY

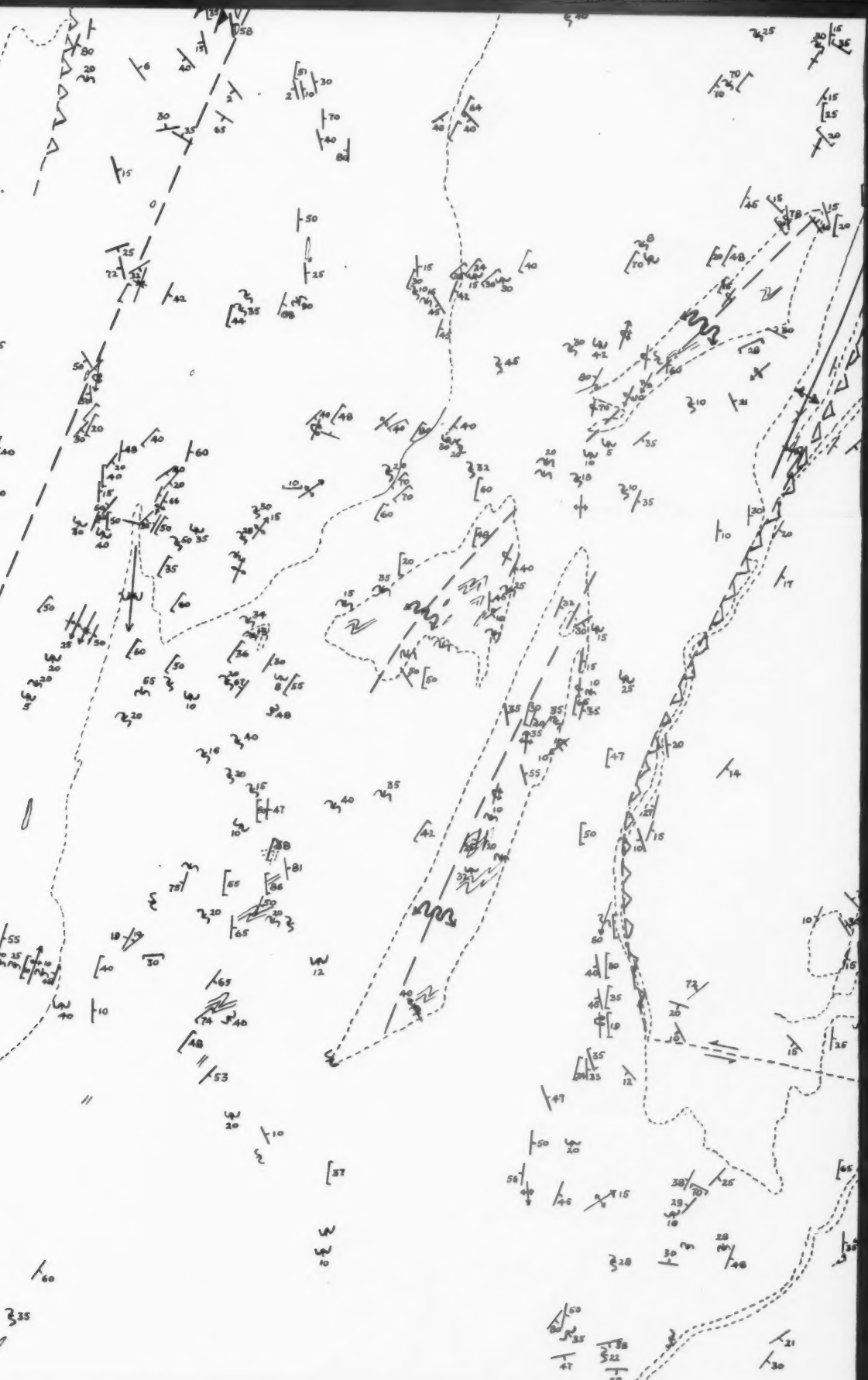
STRUCTURE MAP

OF THE

COPAKE QUADRANGLE, NEW YORK

J.D. WEAVER - 1950-52.





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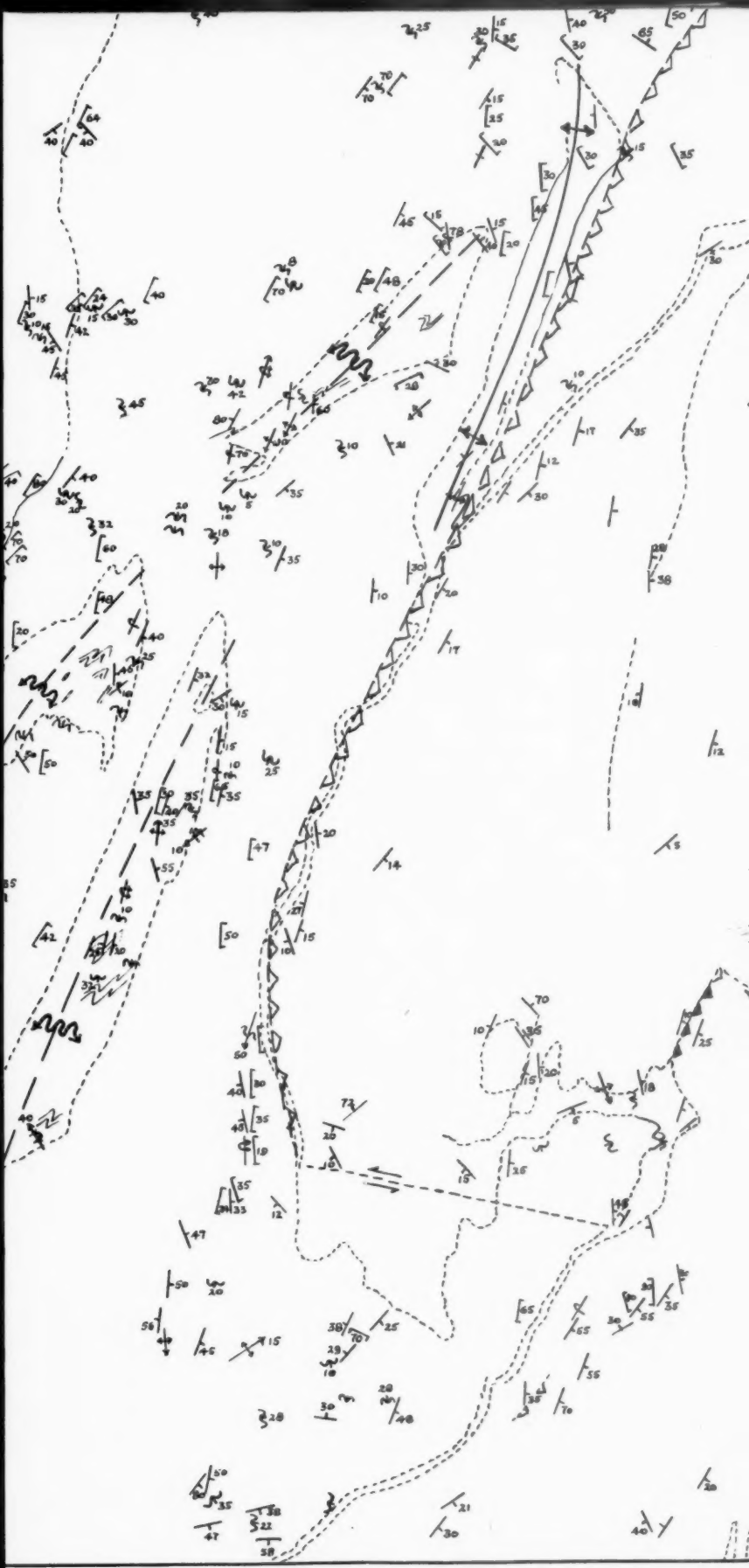

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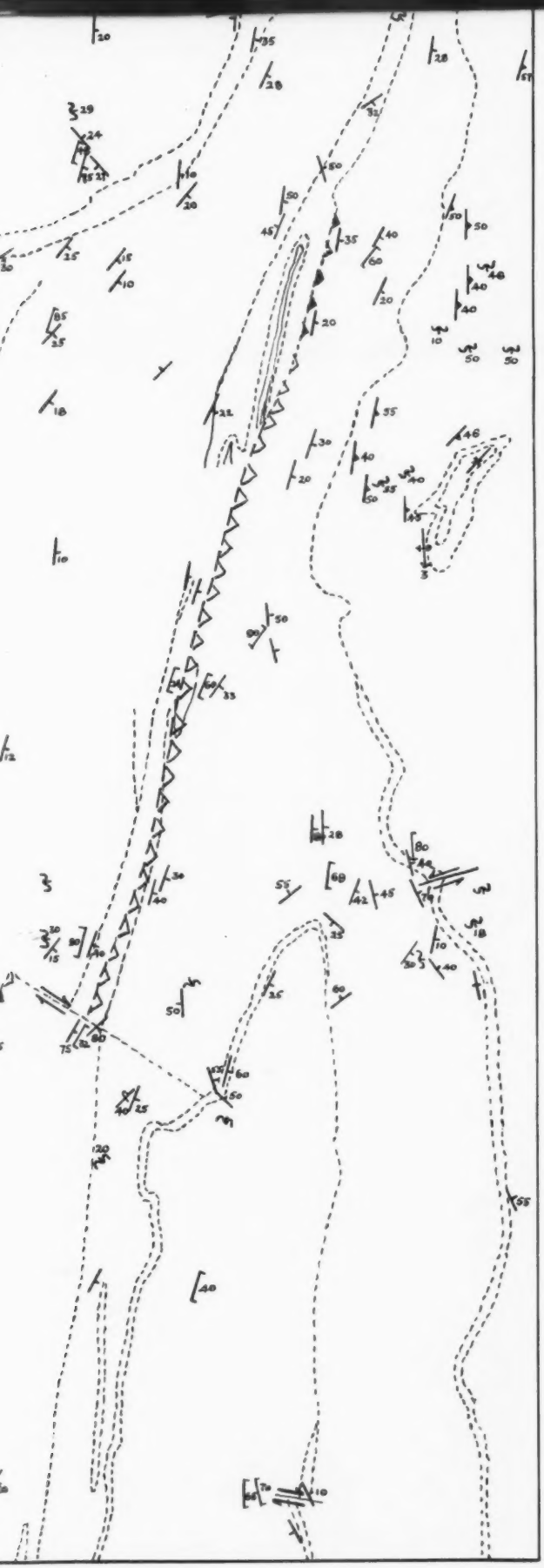

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BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 68, PP. 763-784, 5 FIGS. JUNE 1957

POTASSIUM-ARGON METHOD OF GEOCHRONOMETRY

BY DONALD R. CARR AND J. LAURENCE KULP

ABSTRACT

A brief history of the development of the potassium-argon method of geochronometry is presented and the evidence for the decay scheme is reviewed. A survey of the experimental measurements of the β and γ activity of K^{40} indicates that there is fairly general agreement on a $\lambda\gamma/\lambda\beta = 0.12$.

The isotope dilution technique and equipment employed at the Lamont Geological Observatory for the argon analysis are described. The A^{40}/K^{40} ratio can be determined with an accuracy of better than ± 5 per cent. Radioactive A^{37} has been used as a tracer to check the yield of the liberation and purification procedure. These experiments indicate that within an experimental error of 2 per cent, all the argon present in a sample is released during fusion; that spike equilibration is achieved, and that no argon is lost during purification.

The problem of argon retentivity in various minerals is discussed. For minerals of known age the fraction of argon retained can be calculated. Micas retain about 80–100 per cent of their argon, whereas feldspars vary in retentivity from 40–85 per cent for the samples listed. Much more data are needed to evaluate the possible causes of argon loss.

In the Southern Appalachians K-A ages have been determined for the pegmatites and several host rocks. The micas of the Spruce Pine District pegmatites yield ages of 340 ± 15 m.y. in excellent agreement with U-Pb ages for the same pegmatites (350 ± 20 m.y.). The host rocks give uncorrected ages of about 400 m.y. which when corrected for the argon loss from the feldspars increase to at least 600 m.y. This establishes the primary regional metamorphism which produced the Cranberry, Carolina, and Roan gneisses and the Beech granite as being Precambrian rather than Paleozoic.

In the Bear Mountain area of New York State the K-A ages corrected for retentivity are about 800 m.y. for the Storm King granite and about 1400 m.y. for the Canada Hill gneiss. This proves that the Storm King could not be Paleozoic and suggests that the New Jersey-New York Highlands are older than the Blue Ridge Province of the Southern Appalachians. The spread in ages is interpreted as evidence for the igneous origin of the Storm King granite.

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Introduction

The absolute age determination of a rock unit continues to be a subject of fundamental importance to geology and allied disciplines. Relative ages can be derived from a study of structural relationships and paleontology, but methods based on radioactivity remain the only means of absolute measurements of age. The pace of investigation in the field of radioactive geochronometry has been greatly accelerated over the last decade. New methods have been examined, and the limitations of older methods are now more clearly defined. Nevertheless, no method, except the one based on natural radiocarbon, has been developed to the point where routine analyses can yield reliable ages. Problems of leaching, leakage, or the determination of physical constants remain to some extent in each method.

The decay of K^{40} to form A^{40} is an isotopic chronometer of particular interest. The widespread occurrence of potassium minerals and the relatively high concentration of potassium in basalt which covers a large part of the oceanic area of the globe makes this age-determination method of outstanding geological importance. Further, the method may in principle be applied to minerals of metamorphic rocks such as schist and gneiss. These are the common rocks of vast areas of complex Precambrian geology for which quantitative ages are rare or absent. If techniques and equipment such as are described in this paper are utilized, the K-A method is applicable in principle to potassium-rich rocks and minerals older than 10^7 years and potassium-poor samples older than 10^8 years. The ubiquitous nature of potassium makes the potassium-argon method potentially more useful than either the uranium-lead method or the rubidium-strontium method.

Considerable effort is warranted in establishing and developing the potassium-argon method because of the major contribution it may make to our knowledge of earth history. The purpose of this research was to prove the experimental techniques, to examine various related rocks and minerals to define the limitations of the method, and to make a few applications of the chronometer to important geological problems.

Acknowledgments

This investigation was initiated and largely supported by the generous grants of the Research Corporation. The Research Division of the Atomic Energy Commission provided essential financial aid in the later phases of the program.

Dr. K. E. Lowe provided valuable assistance in discussions of the geology of the Bear Mountain area and in sample collection. Dr. W. G. Guldner and Mr. A. L. Beach of Bell Laboratories, Murray Hill, New Jersey, and Mr. D. Walter of Naval Research Laboratory, Washington, D. C., contributed to the design of the vacuum fusion techniques employed. Helpful discussions were held with Drs. R. D. Russell, R. M. Farquhar, H. A. Shillibeer, G. W. Wetherill, and G. J. Wasserburg who supplied the Dickinson County sample for intercalibration purposes. Professors W. Bucher and Brian H. Mason critically reviewed the manuscript.

L. E. Long, P. E. Damon, W. S. Broecker, M. L. Trautman, and D. R. Carpenter assisted in various phases of the experimental program. P. W. Gast and G. L. Bate offered many useful suggestions with regard to mass spectrometer operation. R. D. Janes, W. P. Knox, W. Tamminga, and M. Gwinner were responsible for the construction, maintenance, and repair of the equipment. F. D. Eckelmann aided in sam-

ple description, and W. R. Eckelmann supplied the information on uranium-lead ages. The help of Mrs. M. Rippey, Miss C. Vath, and Mr. R. Heningham in manuscript preparation is gratefully acknowledged.

Historical Survey

Although the radioactivity of potassium was discovered by Campbell and Wood (1906) near the turn of the century, it was not until 1943 that Thompson and Rowlands proved that the decay of potassium involved the production of A^{40}, although Von Weizsäcker (1937) had earlier predicted a dual decay to Ca^{40} and A^{40}. That K^{40} is the radioactive isotope of potassium had been already shown by Smythe and Hemmendinger (1937), and its abundance was determined by Nier (1935) as (0.011 ± .001) per cent. Little serious work was done even on the decay constants until after World War II. The first successful attempt to show a relation between the A^{40}/K^{40} ratio and age was made by Aldrich and Nier (1948) on two feldspar and two evaporate minerals, sylvite and langbeinite. Their results suggested considerable argon loss. More recently research on the method was initiated at a number of institutions including Department of Physics, University of Toronto; Institute for Nuclear Studies, University of Chicago; Department of Terrestrial Magnetism, Carnegie Institution of Washington; Department of Physics, University of California, Berkeley; and the Lamont Geological Observatory, Columbia University, as well as several European laboratories.

At the beginning of this phase of the development of the method, the branching ratio $\lambda_\gamma/\lambda_\beta$ as determined by physical experiments stood at about .12. Obviously the branching ratio as well as the total disintegration rate and the A^{40}/K^{40} ratio of a mineral must be known in order to measure age.

The decay constants can be calculated if the A^{40}/K^{40} ratio of at least two minerals of widely different known age is measured, and if 100 per cent retention of the argon is assumed. The Toronto group (Farquhar 1953) first reported a geologic branching ratio as .06 on several feldspars ranging in age from 330 to 1800 m.y. Later it was shown that their method of using a sodium metal flux did not effect complete liberation of the argon from the mineral and thus gave a low branching ratio. Wasserburg and Hayden (1955) reported similar experiments on feldspars from four localities that had been dated accurately by the uranium-lead method. Using an NaOH flux and holding aliquots at the melting temperature for varying lengths of time, they concluded that they obtained complete liberation of the argon and suggested a geologic branching ratio of 0.085. Later Wetherill *et al.*, (1955), using an NaOH flux, showed that mica and feldspar from the same locality had different A^{40}/K^{40} ratios. The A^{40}/K^{40} of the mica samples suggested a minimum branching ratio of 0.105. More recent work by Aldrich, Wetherill *et al.* (1956) and at Lamont reported in this paper shows that some micas yield geological branching ratios at least as high as 0.115. This made it apparent that feldspar leaks some of its argon. The "geologic branching ratio" had approached the physical branching ratio, and it appeared that the major remaining problem was to define the limits of retentivity.

This research was started at about the time of the Conference on Nuclear Processes in Geologic Settings at Williams Bay, Wisconsin, in September of 1953. At that time there were major uncertainties in the experimental techniques. Questions were raised such as: which flux, if any, causes complete argon liberation? what was the probability of atmospheric argon contamination? could glow discharges in the furnace, the diffusion pump, or the calcium furnace cause loss of argon in the glass walls? would the presence of stopcock grease cause appreciable argon loss or give rise to memory effects?

One of the major contributions of this work was the development of a flux-free argon liberation system and the successful completion of tracer experiments which indicated quantitative liberation of argon from silicate melts and no subsequent loss in the purification system. The experimental procedures were well established, and it was possible to define the limitations of the method and to apply it in a reconnaissance manner to several geological problems.

Principles

Decay Scheme

The decay scheme for K^{40} based on experimental work and theoretical arguments is essentially that shown in Figure 1. Evidence that would indicate a more complicated decay scheme has been sought in vain (McNair *et al.*, 1955). The energy of the one γ which seems to be associated with potassium decay exceeds the maximum β energy of the Ca^{40} branch (Roberts and Nier, 1950; Nier, 1950) and β-γ coincidences are absent (Meyer *et al.*, 1947; Smaller *et al.*, 1950; Houtermans *et al.*, 1950). Therefore the gamma activity is considered associated with the electron capture to an excited state of A^{40}. (Suess, 1948; Hirzel and Waffler, 1948; Paganelli and Quarani, 1952; Johnson, 1952), and the β decay must be to the ground state of Ca^{40}. Annihilation quanta in the γ-ray spectrum due to positron emission have not been detected (Bell and Cassidy, 1950a; Good, 1951; Colgate, 1951), and the electron capture due directly to the ground state of A^{40} is negligible (Graf, 1948a; 1948b; Sawyer and Wiedenbeck, 1950; Morrison, 1951). The Auger electrons and X rays which have been detected can be associated with the γ decay from the excited state of A^{40}.

In the absence of evidence to the contrary, it seems safe to conclude that the discrepancy between the branching ratios as determined by K-A measurement and counting techniques is not due to an erroneous decay scheme. Therefore, based on this decay scheme the equation for argon accumulation in a mineral is

$$A^{40} = N \frac{R}{1+R} [e^{(1+R)\lambda_\beta t} - 1]^1$$

where A^{40} = the number of A^{40} atoms formed in time t, in years

λ_β = the fraction of K^{40} atoms decaying per year to Ca^{40}

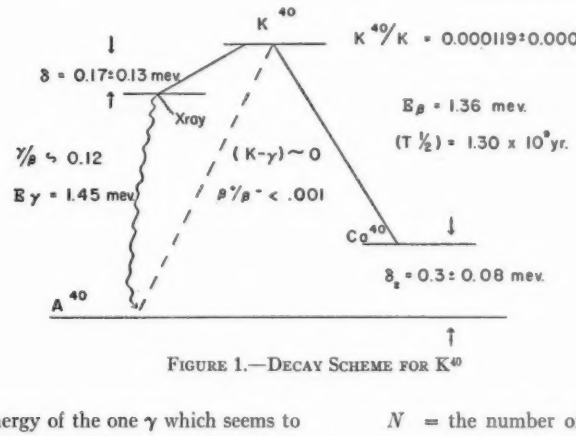

Figure 1.—Decay Scheme for K^{40}

N = the number of K^{40} atoms left at time t

and $R = \lambda_\gamma/\lambda_\beta$

Two assumptions are made: (1) no argon is trapped within the mineral at the time of its formation, and (2) potassium and argon are not added or subtracted during the lifetime of the mineral.

For an age determination, A^{40} and K^{40} are measured, t may then be calculated if the constants R and λ_β are known. However, λ_β and λ_γ and hence R are not known with high precision. Measurements of the γ activity since 1948 range from 2.6 to 3.6 dps/gm K, whereas those of the β activity range from 23 to 34 dps/gm K.

Physical Constants

The decay constant data through 1950 were summarized by Birch (1951) who found that 28.3 β's/sec/gm K was the mean of 12 β determinations. Although he considered the best single value to be 30.6 $\pm$ 2.0 determined by Stout (1949); he adopted the value of 28.3 $\pm$ 1

[1] Friedlander, G., and Kennedy, J. W. (1949)

preferred by Sawyer and Wiedenbeck (1950) for his calculations. The value of 27.1 ± 1.5 β's/sec/gm K of Houtermans *et al.* (1950) though not included in the summary by Birch is consistent with this conclusion. Houtermans' value of 3.1 ± .3 λ's/sec/gm K, however, is much lower than the 3.6 value selected by Birch as the γ-decay rate. Houtermans' value as well as the determination of 3.4γ's/sec/gm K by Ahrens and Evans (1948) might very well be included in a summary of the work through 1950. If these were included and the early values of Kohlhorster (1930), Mühlhoff (1930), and that of Floyd and Borst (1949) were eliminated as being obviously low, a straight average of the γ determinations in Birch's Table 1 would give 3.4 γ's/sec/gm K.

Endt and Kluyver (1954) in their review of the β-decay constant calculate an average of 27.6 β's/sec/gm. Their summary includes the work of Houtermans *et al.* (1950) and Good (1951). The measurements made with enriched targets (Borst and Floyd, 1948; Floyd and Borst, 1949; and Sawyer and Wiedenbeck, 1950), however, are not included since the uncertainty in the isotopic concentration gives these values less precision. An evaluation of the λ-ray value by Endt and Kluyver is based on only seven determinations, three of which are different from those cited by Birch. In spite of this the average is still 3.4 γ's/sec/gm K.

A recent summary (Carr *et al.*, 1955) includes all the independent β and γ determinations from 1948–1954 with the exception of McNair *et al.* (1955). The mean values are 28.6 ± 0.9 and 3.33 ± .09; the low γ value of Floyd and Borst (1949) is omitted. This agrees very well with the recent work of McNair *et al.* (1955) who obtained 27.6 ± .4 β's/sec/gm K and 3.4 γ's/sec/gm K and the mean γ value of 3.50 obtained by Backenstoss and Goebel (1955) by comparison with Pr^{142}, Co^{60}, and Fe^{59}. The work by Suttle and Libby (1955) gave a β value of 29.6 ± .7 which though somewhat higher is not inconsistent with these average values.

The list of γ determinations in the summary of Shillibeer and Russell (1954) is rather limited and gives an average of about 3.2–3.3 γ's/sec/gm K. The value obtained by Sawyer and Wiedenbeck (1949) was recalculated by Wasserburg and Hayden (1954) from 3.6 ± 1.2 to 2.9 ± 3 based on the determination of the K^{42} branching ratio by Kahn and Lyon (1953). A more recent measurement by Emery and Veall (1955) makes the recalculation questionable because of the uncertainty in the decay scheme of K^{42}. (Bleuler and Zunti, 1947; Siegbahn, 1947; Siegbahn and Johansson, 1947). The ratio of $\lambda_\gamma/\lambda_\beta$ from Shillibeer's summary is 0.11 in contrast to the 0.090 derived by taking the mean of the branching ratios back to 1930. In view of the geologic measurements to be discussed later, the 0.090 branching ratio is definitely low.

All the summaries are in substantial agreement and are near the most recent and elaborate measurements by McNair *et al.* (1955) and Backenstoss and Goebel (1955). Therefore, β- and γ-decay constant of 27.6 β's/sec/gm K and 3.4 γ/sec gm K have been chosen for the calculation of the results in this study[2]. These values give a branching ratio of 0.123 and a λ_β of 0.476×10^{-9} yr.$^{-1}$. If the Suttle and Libby (1955) β determination of 29.6 β's/sec/gm K is used with 3.4 γ's/sec/gm K the resulting branching ratio is 0.115 and the λ_β is 0.508×10^{-9} yr.$^{-1}$.

The curve shown in Figure 2 serves to show the variation of t with changes in A content. The argon content would not give the true age of the sample if (1) argon was trapped in the sample at the time of formation, (2) argon was added or lost during the lifetime of the sample, or (3) the analysis was in error. It is unlikely that factors (1) and (3) present any significant problem, but it has become clear from the results of this investigation that argon can be lost from some minerals in variable amounts. An incorrect potassium value might be due to loss or addition of potassium, faulty analysis, or incorrect isotopic abundance values. The possibility of an appreciable error in the isotopic abundance of potassium is rather remote. Nier's value of (0.0119 ± .0001) per cent (1950) has been checked by Reutersward (1951) who obtained (0.0118 ± .0001) per cent. Potassium loss or gain does not seem likely with unweathered fresh potassium minerals.

[2] At the AAAS symposium on Geochronometry in New York City December 1956 Dr. George Wetherill, using a scintillation counter technique and calibration with Ca^{60} and Na^{24}, reported a new measurement of 3.38 ± 15γ's/sec/gm K.

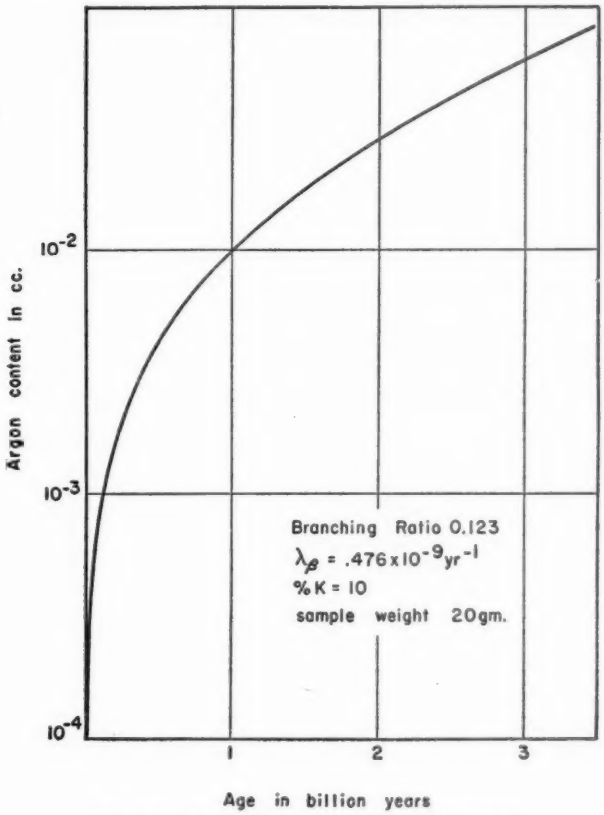

FIGURE 2.—ARGON CONTENT AS A FUNCTION OF AGE

ANALYTICAL TECHNIQUES

General Outline

The potassium-argon method requires the quantitative determination of both elements in the mineral sample. The potassium analyses were done by wet chemical methods which gave a precision of ±2 per cent in most cases. The results of these wet methods and the flame photometric and isotope dilution techniques employed by other laboratories indicate that the uncertainty of the potassium determination is probably ±2 per cent although in some cases it may approach 5 per cent.

The argon determination involves quantitative release of the argon from the sample, purification, and mass spectrometric measurement using isotope dilution techniques. Tracer studies using argon 37 indicate that liberation is complete and purification is accomplished without loss of argon. Duplicate analyses show the argon determination to have a precision of about ±3 per cent. Interlaboratory comparison indicates that the accuracs better iy than ±5 per cent in nearly all cases.

Potassium Analyses

The potassium analyses made by Ledoux and Company followed a procedure which is a modification of that described by Kallman (1946). The sample is digested with hydrofluoric acid, perchloric acid is added, and after a steam distillation process to eliminate fluorides and prevent the loss of KAlF, the solution is evaporated to near dryness. The addition of butyl alcohol and ethyl acetate to the cool perchlorates precipitates potassium perchlorate and effects the separation of sodium, which remains in the supernatant liquid. The separation is repeated, and the potassium content calculated from the weight of the dried potassium perchlorate. This calculated potassium content also contains any rubidium and cesium present. The rubidium deter-

mination is made by converting the final potassium perchlorate to sulfate and comparing it on an emission spectrograph to standard mixtures of potassium and rubidium sulfate made from pure chlorides.

All analyses were run in duplicate and a Bureau of Standards potassium feldspar was analyzed with each group of samples as a standard. The agreement with the standard was better than 2 per cent. Samples were split and sent to the analyst over a period of several months. Results indicative of a precision of about ±2 per cent are given in Table 1. It is probable that the error in the accuracy does not greatly exceed the precision.

TABLE 1.—REPRODUCIBILITY OF POTASSIUM ANALYSES*

	Aliquot no. 1	Aliquot no. 2
Canada Hill Granite	1.32	1.27
Deep Creek Mica	3.13	3.00
Black Hills Lepidolite	8.52	8.24
McKinney Mica	8.17	8.30
McKinney Feldspar	10.80	10.84

* Each value given is the average of duplicate analyses; Analyst: Ledoux and Co., Teaneck, N. J.

Wetherill, Wasserburg, *et al.* (1956) report that analyses by isotope dilution and flame photometry agree within about 5 per cent or better. In the analyses reported by Wasserburg and Hayden (1955), the errors given vary up to about ±2 per cent for samples having low potassium content. Shillibeer has reported intercomparison between two analysts using flame photometry and U. S. National Bureau of Standards feldspars. The results on four samples show agreement to ±0, 1, 2, and 7 per cent; the highest error is on the sample of lowest potassium content. It would appear then from the results of different laboratories that the potassium content can be ascertained to better than 5 per cent.

A^{40} Determinations

Introduction.—The A^{40} determination involves the release of the argon in the rock by a direct fusion technique without a flux (Guldner and Beach, 1950), equilibration with the spike A^{38}, purification, and finally mass spectrometer measurement (Aldrich and Nier, 1948).

Most laboratories have been fusing the sample with a flux such as Na, NaOH, Na_2CO_3, or Na_2CO_2. Shillibeer and Russell (1954) show that the quantity of argon liberated when Na is used varies with the grain size until a maximum is reached at 250 mesh. At this point Na and NaOH effect approximately the same removal. However, if the fusion process is flux dependent, then it is conceivable that fusion without a flux might release additional quantities of argon. If the same amount of gas is released as with a flux, then the possibility of incomplete liberation becomes less likely. Further, if a tracer argon isotope (A^{37}) can be released inside a silicate melt and quantitatively recovered, complete liberation of the A^{40} can be assumed.

Direct fusion apparatus.—The furnace assembly for sample fusion is shown in Figure 3. It consists of a quartz tube 2 inches in diameter and 12 inches in length with a 60/50 ground glass joint at the top. The female joint and the rest of the furnace assembly is of pyrex glass. A molybdenum crucible 1 inch in diameter and 2¼ inches in length and containing the sample is suspended by platinum wires about 1½ inches from the bottom of the quartz tube. The crucible is made of 010-inch sheared, deep-drawing molybdenum. The top and bottom caps are drawn so that they slip tightly over the cylindrical center portion. The bottom cap is held on by several indentations around the bottom made after assembly. For samples which contain little or no mica, a top cap which has a ¾-inch hole is used. Mica samples tend to jump out of the crucible, and therefore a number of small holes ~ a sixteenth of an inch in diameter are drilled through the top cap instead of one large hole. Sharp edges must be filed off to avoid arcing during the heating.

The crucible is the secondary for a 5 kw Westinghouse radio-frequency generator. The water-cooled primary consists of 11 turns 3 inches in diameter of quarter-inch copper tubing spaced about an eighth of an inch apart. The entire primary coil is within 2 feet of the generator to insure that the unit will not violate Federal Communications Commission regulations. This question arises because the 450-kc output and the harmonics are within the broadcast band.

A sidearm above the ground joint is the point of introduction of the A^{38} into the system. A prism assembly at the top of the furnace allows observation and temperature measurement of the fusion process throughout the heating cycle. Temperatures are estimated with a Leeds and Northrop optical pyrometer.

Argon liberation and purification procedures.—Samples free from obvious defects such as gross fracturing or alteration are crushed so that fragments are below an eighth of an inch. All the crushed sample is saved, but the portion greater than 60 mesh is divided in a sample splitter. Representative samples for fusion and potassium analysis are taken

from this portion. Samples weighing as much as about 60 gms could be fused with the crucibles described, but the usual size is about 20 gms. After the sample has been placed in position and the break seal containing A^{38} has been blown on, the furnace assembly is evacuated overnight.

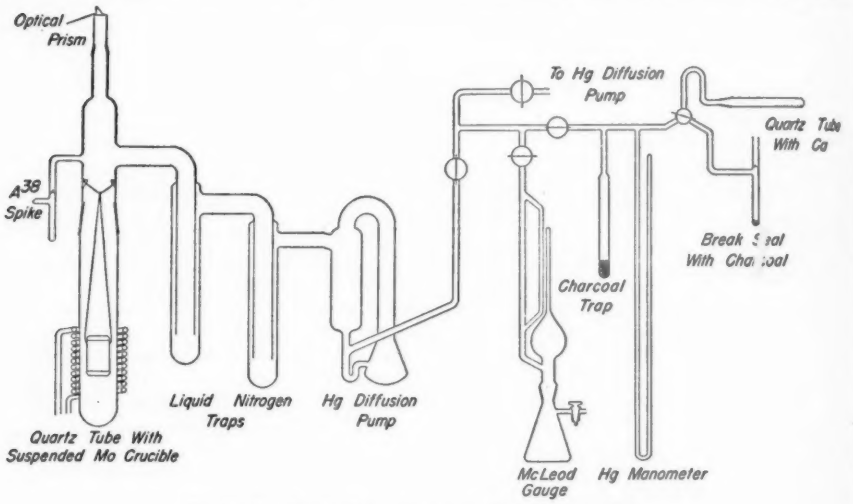

FIGURE 3.—ARGON LIBERATION AND PURIFICATION SYSTEM

The charcoal trap containing about 10 gms of activated charcoal and the break seal containing about 1 gm of activated charcoal for the final collection of the argon sample must also be baked out for several hours at about 350°C. under vacuum. This degassing of the charcoal is also accomplished overnight. Aluminum foil protects the stopcocks during the heating.

The calcium used for purification of the gas from the rock (Dushman, 1949) is contained in a quartz tube 6 inches in length and half an inch in diameter; a 10/30 ground glass joint is at one end and the other end is closed. About 5 gms of fresh calcium filings from a lump of electrolytically pure calcium are used for each run. The calcium is also preheated for several hours under vacuum at about 350°C.

Evacuation and baking are continued until the entire system is at a pressure of about 10^{-6} mm. At this point the system is ready for operation. Blank runs have shown that preheating of the furnace assembly is unnecessary. Liquid nitrogen is put on the traps between the furnace and diffusion pump to prevent Hg vapor from entering the furnace. The diffusion pump is turned on, and at the same time liquid nitrogen is put on the charcoal trap. After the diffusion pump has begun to operate, the system is isolated from the main mercury diffusion pump and the furnace mercury diffusion pump now exhausts to the charcoal trap. The calcium and the break seal are isolated from the system and each other. Cooling water, power to the generator, and blowers to cool the furnace joint are turned on. The heating schedule is not fixed, but in general a temperature above 1400° C is reached within half an hour. This temperature is then maintained for half an hour. Longer heating at higher temperature has failed to release more argon. The mercury diffusion pump operates throughout the fusion, removing the gases released, and discharging them to the charcoal. When the sample fragment outlines become blurred, the A^{38} is released from the break seal into the furnace assembly. The seal is broken within the vacuum by means of a glass enclosed nail and a magnet. The A^{38} is drawn out of the furnace through the pump and adsorbed on the charcoal with the other gases. After the half-hour fusion above 1400 C, the power is turned off, but the diffusion pump continues to operate for another 20 minutes while the furnace assembly cools. The charcoal is then isolated from the rest of the system and the liquid nitrogen removed. The pressure increases from 0 mm as read on a manometer to from 15 to 200 mm in a volume of 100 cc depending on the water content of the sample. The pressure for feldspar samples is usually 15–30 mm, whereas that for micas ranges from 30 to 200 mm. The different pressures are probably due to hydrogen from the dissociation of water. The calcium furnace is turned on and the variac set so that the temperature reaches 750°C.–800°C. in about 20 minutes. At this

time the charcoal trap has warmed to room temperature, and the pressure has reached a maximum. The gases are then admitted to the hot calcium, and the pressure drops over a period of 2–5 minutes to 0 mm on the manometer. Liquid air is then put on the charcoal trap, and the break seal and the calcium furnace is turned off. Hydrogen is not completely removed by calcium (Dushman, 1949), and therefore some remains with the rare gases after this purification procedure. Twenty minutes are allowed to move the argon back out of the calcium tube and onto the charcoal. The three-way stopcock is then turned so that the charcoal trap and the sample collection break seal are interconnected and the calcium tube is isolated. The liquid nitrogen is then removed from the charcoal trap, and another 20 minutes are allowed for the argon to move over onto the charcoal in the break seal. The break seal is then closed with a torch and removed from the system for transfer to the mass spectrometer inlet system in another room.

A series of runs have been made to determine the background of the argon collection system. Complete blank runs made with an empty crucible gave peaks at mass 40 of less than 2.5 mv at low pressure in every case. This would amount to less than 2 per cent contamination for the Spruce Pine feldspars. The amount of atmospheric argon which might be adsorbed on a finely ground sample was tested with a pure Spruce Pine albite. Again the mass 40 peak was less than 2.5 mv and therefore within the equipment background value. A Spruce Pine feldspar was heated for half an hour at 800°C. as a check on the ease with which argon could be released. Under these conditions about 20 per cent of the total argon was liberated. A second and third heating of the same sample under the same conditions without opening the furnace assembly yielded less than 1 per cent additional argon. The sample was finally fused and the remaining 80 per cent liberated, since two more complete fusion runs at higher temperatures were made on the resulting glass and no further argon was released. These preliminary tests indicated that the fusion procedure was satisfactory.

A^{37} tracer experiments. —In view of the differences in technique used at different laboratories and the absence of definitive answers to questions of argon behavior in small quantities in vacuum systems, it was decided to investigate these problems using A^{37} ($T - 1/2 = 35$ days) as a tracer (Carr and Kulp, 1955).

The specific questions to be answered were:

(1) In the furnace assembly and purification system described above, is argon lost by sorption on glass walls or in the stopcock grease to any appreciable extent?

(2) Can the argon be absorbed on charcoal quantitatively and held there while the system is evacuated? If so, can it then be desorbed quantitatively?

(3) Can appreciable quantities of argon be driven into the walls or lost in other ways in the RF furnace, the mercury diffusion pump, or the calcium cleanup furnace?

(4) Is all of the argon released from the sample during fusion? The results of A^{37} counting experiments are given in Table 2.

TABLE 2.—EXPERIMENTS WITH A^{37}

Experiment	Predicted cpm assuming no loss of argon	Actual cpm
1 adsorption	1462 ± 12	1469 ± 8
2 pumping	1109 ± 10	1113 ± 11
3 circulation	629 ± 8	622 ± 8
4 circulation	580 ± 6	584 ± 6
5 A^{37} capsule + feldspar fused	1146 ± 20	1187 ± 16
6 A^{37} capsule + feldspar fused	875 ± 22	909 ± 11
7 A^{37} capsule fused	1544 ± 20	1510 ± 19
8 A^{37} capsule + feldspar fused	1446 ± 20	1400 ± 20
9 A^{37} capsule fused	1537 ± 20	1510 ± 19

In experiment (1) an aliquot of A^{37} was counted, while another of the same size was allowed to stand for 3 hours in a system with seven stopcocks and a ground glass joint. Then the second aliquot was drawn into the counter. The net count was doubled as would be predicted if there were no loss of argon to the glass or grease. Experiment (2) tested the capacity of charcoal to hold argon at liquid nitrogen temperature by counting a sample volume, then freezing it out on the counter charcoal trap and pumping on it with a mercury diffusion pump. A 2-minute pumping test gave 1108 ±7 cpm before pumping and 1111 ± 10 after pumping. The test was repeated with a pumping time of 15 minutes. The result given in Table 2 shows that no appreciable quantity of argon was evacuated.

For experiment (3) an aliquot of A^{37} was counted, then introduced with the filling gas into the RF furnace, circulated through the system and purified the same way as gases from a rock except as noted. Finally it was collected in the Geiger counter, connected at the place where the purified rock argon would normally be collected in a break seal, and recounted with new ethylene. The run differed from the normal procedure in that the induction furnace

was not heated, and the Ca furnace was heated without calcium. Table 2 gives the predicted and actual counts per minute after circulation. No appreciable loss of A^{37} could be detected.

A similar experiment (4) was conducted in which the induction furnace was heated until there was a mercury discharge in the furnace caused by incomplete removal of the vapor before the run. This was the phenomenon which has been suggested as a mechanism for driving argon into the glass walls. In addition calcium chips were put in the calcium furnace which was heated to 720°C. In the third experiment the A^{37} and the filling gas mixture of argon and ethylene were transferred from the counter to the system and circulated together. It was thought that the large amount of carrier gas might mask effects which would be troublesome when dealing with argon on the order of 10^{-2}–10^{-4} cc (STP) such as is the case in an actual run with a rock sample. Therefore, in experiment (4) an aliquot of A^{37} was counted while a similar one having a volume of 10^{-9} cc at STP was circulated alone. The former is given in Table 2 as the predicted value. After circulation the latter was drawn into the evacuated counter, filling gas was added, and it was counted. This value is given as the actual count rate. The two values are the same and prove that less than 2 per cent could have been lost in circulation.

For experiments 5–9 pyrex capsules were prepared and sealed with a known quantity of A^{37} determined by counting and fused in a crucible. In experiments 7 and 9 the capsules were fused alone to study their behavior, whereas in experiments 5, 6, and 8 the capsule was buried in a powdered feldspar sample and both were fused. In each experiment the argon was collected and purified. It was then counted to determine the recovery. The capsules when fused alone collapsed. When they were buried in a sample, there was no indication that the A^{37} was released from the capsule before the sample as a whole was fused. The results of the fusion and purification train tests are shown in Table 2. Again essentially complete recovery indicating complete liberation of the argon was obtained. Since these experiments indicate that complete liberation of the argon occurs with the direct fusion method, it is of interest to compare the result with that of a flux method. The agreement of the analyses on aliquots of the Dickinson County feldspar by Wasserburg using an NaOH flux, and the present direct fusion method shows that the NaOH flux method is also liberating all the argon. Quantities of argon as small as 10^{-9} cc can be circulated in a vacuum system containing a rock melt in an RF furnace, an Hg diffusion pump, hot Ca, charcoal traps, and stopcocks with less than 2 per cent loss. Therefore, an argon measurement could be made volumetrically if purification was complete every time. Since an examination of the isotopic composition of the argon is desirable to check against possible atmospheric argon contamination, however, it is reasonable to apply an isotope dilution technique with A^{38}.

Preparation of A^{38} Spike

The handling of the A^{38} spike is a very critical part of the technique. The A^{38} spike obtained from Oak Ridge was expanded into several storage bulbs, and 29 break seals of known volume in the system shown in Figure 4. The volume of each break seal was determined previously with mercury. Connections to the vacuum system, McLeod gauge, mercury reservoir, and break seal manifold are also shown. This system is similar to that described by Hayden and Inghram (1953). The construction of the manifold with the break seals projecting into it was suggested by a spike system used by Silvio Balestrini (1954) in Xe studies. When the mercury is raised to various levels, the vacuum lead, McLeod gauge, A^{38} container, and finally all the individual A^{38} break seals can be isolated. The essential requirement of such a system is that the break seals be positioned so that they are at the same pressure when isolated. They are then sealed off with a torch. One of the break seals is used to compare the isotopic composition of the gas in the break seals with that in the original spike container as received from Oak Ridge. Break-seal bulbs of spectroscopically pure atmospheric argon of known pressure and volume were prepared and run on the spectrometer with two tracer break seals to determine the pressure in all 29 spikes. For each pressure measurement, the tracer break seal and the break seal containing atmospheric argon were equilibrated before admission to the spectrometer.

The first two checks of the first set of spikes gave a 7 per cent difference. The pressure of the atmospheric argon standards with which these were compared was measured with a McLeod gauge. Apparently one bulb leaked before the McLeod gauge reading was taken. Thus the pressure measured was due partly to air, and the A^{40} present was actually less than would be calculated from the pressure. Another system was built so that the pressure could be measured in cm on a manometer and then reduced by expansion into a large known volume. Two more calibration runs were made with this technique, and the result was that the pressure in the first set of spikes was determined to be .190 ± .004 mm. Two break seals from the second set of spikes were compared in the same

manner. The pressure, .128 mm, was the same for both break seals.

For each argon determination one of the spikes whose pressure and volume are now known is blown onto the furnace. As the sample is melted, the A^{38} spike is opened and the A^{38} and A^{40} from potassium decay are pumped out of the furnace and circulated through purification train together. The A^{37} tracer experiments show that the 38 and 40 will equilibrate with this procedure, and that there are no memory effects from one run to the next. Argon 40 once released will not reenter the melt since the diffusion pump is operating throughout the fusion period to remove all the released gases from the furnace region.

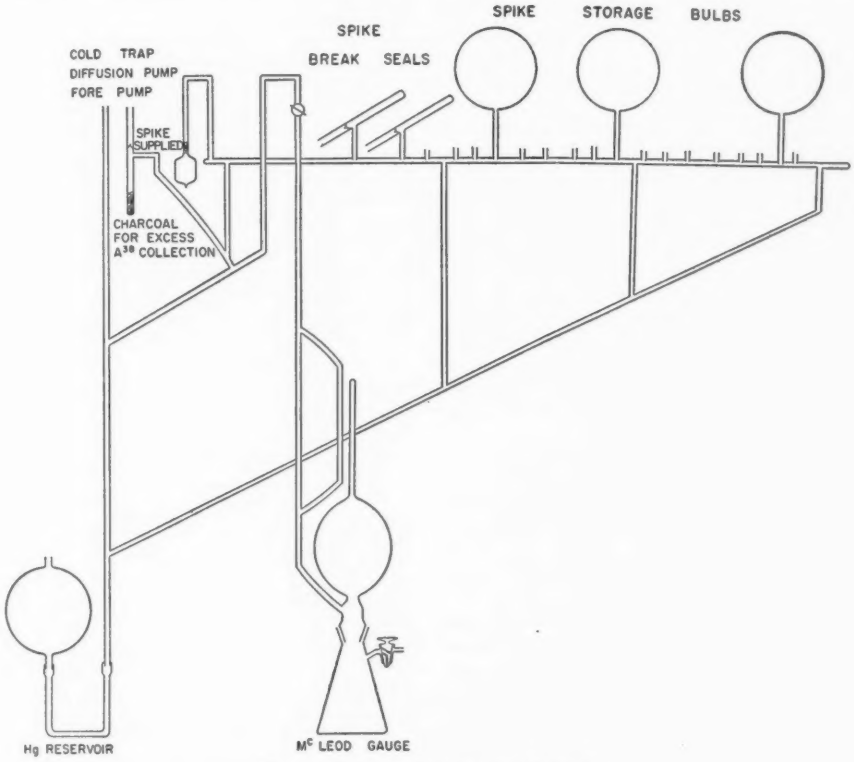

FIGURE 4.—SPIKE PREPARATION SYSTEM

Mass Spectrometer

The spectrometer used for the measurement of the argon is a first-order direction focusing, 60°, 6-inch radius of curvature, magnetic analyzer, mass spectrometer (Nier, 1947). The source and collector end are glass and are attached to the metal analyzer section with Kovar seals. The single pumping lead is near the source. Figure 5 is a block diagram of the mass spectrometer and inlet system. The emission regulator, high voltage supply, and magnet power supply are conventional units. The source is essentially that described by Palmer and Aitken (1952) simplified by the elimination of the first collimating slit and the centering plates and machined to allow introduction of the gas from the leak. Normal operation conditions are about 3 amperes through the .001-inch by .025-inch tungsten filament and an ion accelerating voltage of about 2000 volts. Permanent magnets serve to align the beam of 70-volt electrons in the ionizing region. The main magnet has a tripod support in a carriage which can be moved back from the spectrometer tube for purposes of baking. The signal at the collector end is amplified with an Applied Physics Corporation Model 30E vibrating reed electrometer and fed to

a Leeds and Northrup pen and ink recorder which has a 1-second response time. The pickup for the reed is shielded with a brass envelope and aluminum foil. The noise level was $<.02$ mv on the recorder with a 10^{11}-ohm input resistor.

A two-stage mercury diffusion pump backed up by a Welch Duo Seal oil pump is used to evacuate the analyzer tube through two liquid air traps. A dry ice trap is located between the oil pump and mercury pump to help prevent the oil vapors from entering

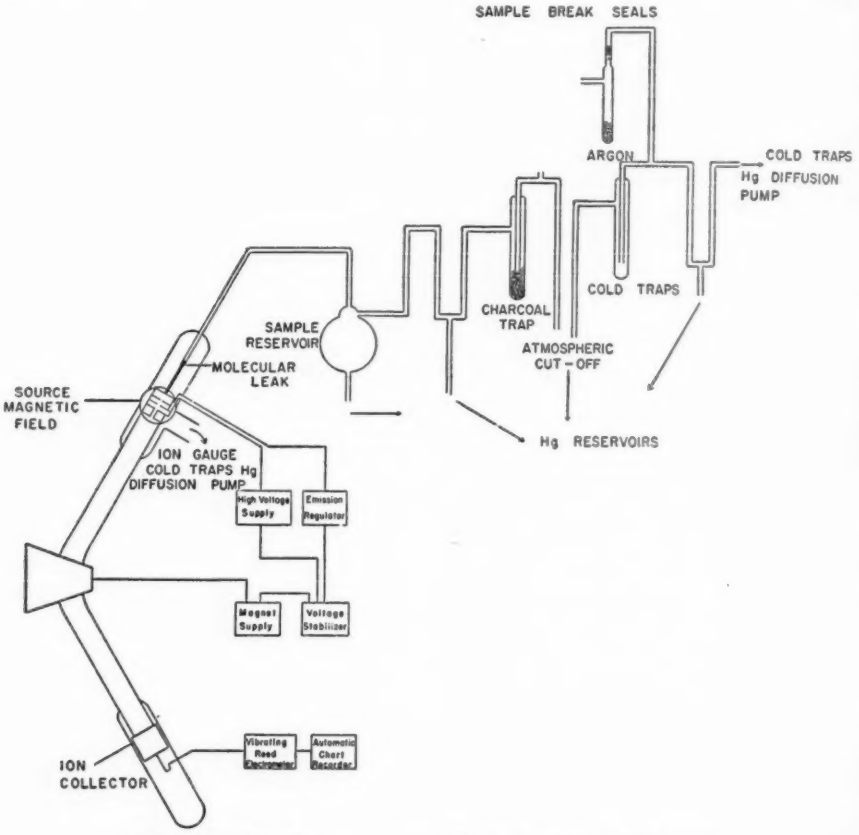

FIGURE 5.—MASS SPECTROMETER AND SAMPLE INTRODUCTION SYSTEM

Scanning is accomplished by variation of the magnet field strength automatically. The speed of scanning can be changed by a factor of 10 to allow slow scanning over the peaks and fast change of field strength between peaks. The 10^{11}-resistor makes the time constant and the scanning speed must be low to develop the full peak height. Varying the speed of scanning makes it possible to scan slowly over the top of the 38 peak four times, move rapidly to the 40-mass peak, and scan over that slowly four times within a 2-minute period. A slip clutch between the 10-turn helipot and the driving motor makes manual changes of the field strength possible independent of the automatic scanning.

the mass spectrometer tube. The normal vacuum attainable is about 2.5×10^{-7} mm gauge, limited probably by the ionization gauge located between the two traps.

The drift with time of the zero using a vibrating reed has been negligible, and therefore no correction in the calculation has been necessary. In any case the experimental practice of going over each peak several times up and down mass and then finally reducing all the data to a peak height versus time curve tends to cause the drift effect to cancel.

Spectroscopically pure argon and neon have been introduced at intervals to check for mass discrimination. The background at mass 36 makes it diffi-

cult to obtain high precision for the A^{36} abundance. The results of the runs agree with the abundances determined by Nier (1950) to within 2 per cent at mass 36. The background at mass 36 decreases slowly with continuous pumping and frequent baking and for most runs is less than .1 mv.

Failure of the power supply to the laboratory allows diffusion of oil vapor from the fore pump into the spectrometer tube. The tube has been swept with the rare gases and nitrogen with very little increase of background. Hydrogen, on the other hand, seems to replace other atoms on the walls of the source region, and the background is appreciably increased. In several runs in which the hydrogen in the sample was not effectively cleaned up, the correction for atmospheric argon was impossible owing to the increase in the 36 peak. In these cases the argon was held on charcoal in the spectrometer introduction line while the hydrogen was pumped off (Chackett *et al.*, 1950). When the hydrogen-free sample was introduced to the spectrometer again, the background remained low. The A^{38}/A^{40} ratios determined before and after hydrogen cleanup were the same and verified the results of Argon 37 tests which showed that argon and hydrogen could be separated in this manner without loss of argon (Carr and Kulp, 1955).

The performance of the mass spectrometer is also shown by the reproducibility obtained. In cases where the same gas sample has been run then frozen back and reintroduced, the 40/38 ratio has been unchanged to within 1 per cent. This has been true whether the sample was introduced the same day or several days later.

Isotopic Analysis

In reference again to Figure 5, the sample break seal is blown onto the system as shown. An atmospheric cutoff allows the sample to be blown on without affecting the vacuum in the spectrometer tube or sample reservoir. The inlet system is then evacuated. The spectrometer tube background and the background of the inlet system are scanned before a run. After the peak heights of 36, 38, and 40 have been determined, the charcoal trap, liquid-nitrogen trap and sample break seal are isolated from the spectrometer tube and the inlet system diffusion pump and trap. Liquid nitrogen is put on the first trap, then about 15 minutes later on the charcoal trap. After a 20-minute period during which the charcoal gets down to temperature, the sample break seal is opened using a glass enclosed nail and a magnet. At least half an hour is allowed for the sample to be adsorbed on the charcoal. The atmospheric cutoff is then raised and the liquid nitrogen removed from the charcoal. The charcoal warms to room temperature in about 20 minutes. During this period, final scans are made of the background. The charcoal trap is then opened to the 300-cc sample reservoir with the mercury at the bottom of the bulb.

The sample flows from the reservoir through 6-mm I.D. tubing to the leak which is about .001 inch in diameter. A .002-inch leak was tried and proved to be too large. The peak heights decrease rapidly with time, and the 40/38 ratio changed appreciably during a run. With the smaller leak the peak heights change by only about 5 per cent in an hour, and the ratio changes by less than 1 per cent. When the sample reservoir pressure is increased by a factor of 5, the curve of peak height versus time remains an essentially straight line function.

The pressure as read on the spectrometer pumping lead usually reaches a maximum value in about 2 minutes. At this time the charcoal is isolated from the system. Scans of the 36 peak are made immediately to check the increase due to sample introduction. After this has been determined, about 12–20 sets of 40–38 peaks are scanned. The direction of scan is reversed several times on each peak to eliminate possible discrimination. The 36 peak is then scanned again and monitored while the mercury is raised in the sample reservoir. In some cases the mercury is raised to the middle of the bulb and the 36/38 ratio checked before raising the pressure further. The peak heights with the mercury at the neck of the sample reservoir are between 5 and 6 times higher than they are with the mercury at the bottom of the bulb. Scans of the 36, 38, and 40 peaks are made at high pressure. The sample is then frozen back onto the charcoal while sitting on top of the 36 peak. In some cases, the 36 peak has failed to drop all the way down to the pre-run background value and indicates that there had been an increase in the 36 peak which was not due to atmospheric argon contamination of the sample. All these observations are used in assessing the atmospheric argon contamination which in almost all cases is less than 3 per cent; *i.e.*, more than 97 per cent of the A^{40} is radiogenic.

Results

North American Localities

All the measurements made in the course of this investigation are listed in Table 3. Each measurement requires about a man-week of effort. The particular samples were chosen for purposes of calibration, determinations of retentivity, interlaboratory comparisons, or for their bearing on important geological problems

TABLE 3.—SUMMARY OF ANALYTICAL RESULTS FROM THIS STUDY
Branching ratio = 0.123; $\lambda_\beta = 0.476 \times 10^{-9}$ yr.$^{-1}$
(Probable uncertainty ±5% of apparent age)

Locality	Rock or mineral	Per cent K	A^{40}/K^{40}	Apparent age (m.y.)
Spruce Pine District, N. C.				
Hoot Owl Pegmatite	feldspar	10.32	.0176 .0179	278
	mica	8.69	.0213	332
McKinney Pegmatite	feldspar	10.80	.0144 .0152	231 242
	mica	8.24	.0213 .0223	329 346
Minpro Pegmatite	feldspar	10.56	.0156	248
	mica	8.97	.0218	338
Mars Hill Pegmatite	feldspar	11.6	.0184 .0187	290 293
Other Southern Appalachian Rocks				
Cranberry				
Independence, Va.	gneiss	3.49	.0263	402
Valle Crucis	gneiss	4.37	.0246	378
Carolina				
Near McKinney Mine	gneiss	2.31	.0246	378
B. R. Pkway. overlook 237 mi. marker	gneiss	1.35	.0240	368
Henderson				
Near Hendersonville, N. C.	gneiss	4.91	.0164	260
Beech				
Rte. 19E, 1 mi. W. of Roan Mt., N. C.	granite	3.97	.0273 .0258	413 394
Bryson City, N. C.				
Deep Creek Mine, No. 1	feldspar	10.75	.0182 .0189	287 296
	mica	3.11	.0378 .0366	555 535
Bear Mountain, N. Y.				
Storm King	granite	4.28	.0367	535
Storm King	pegmatite	7.39	.0365	535
Canada Hill	granite gneiss	1.31	.0886	1110
Pegmatite within the Canada Hill phase		4.06	.0458	655

TABLE 3. (*Continued*)

Locality	Rock or mineral	Per cent K	A^{40}/K^{40}	Apparent age(m.y.)
Black Hills, S. D.				
Ingersoll Mine	lepidolite	8.24	.117	1360
			.120	1390
	microcline	11.82	.0755	980
Wilberforce, Ont.				
Fission Mine	antiperthite	3.73	.0559	770
Dickinson Co., Mich.				
SE ¼ SE ¼ sec. 14 T-42N R-29W	microcline	9.46	.0936	1430
Wind River Canyon, Wyo.	microcline	8.68	.160	1680
Huron Claim, Manitoba	plag. feldspar	0.52	.0969	1180
Gunnison Col.				
Brown Derby Mine	feldspar	10.36	.0618	835
			.0635	855
	lepidolite	7.72	.1173	1360
Combermere, Ont.	feldspar	10.33	.0450	640

which were subject to solution by the precision currently available in the technique.

The numerous repeat runs on the same powder show that the reproducibility in the A^{40} determination lies in the range of $\pm$ 1–3 per cent in most cases. Since this is also the range of variation of the replicate potassium analyses, the analytical error in the A^{40}/K^{40} ratio probably does not exceed 5 per cent. In two cases repeat runs were made on samples of the same rock type collected from different localities (Cranberry and Carolina gneisses). Here the difference between separate samples is only 3 per cent in one case and 7 per cent in the other, and suggests similar mineral composition and similar retentivity.

A sample from a pegmatite from Bonneville, Wyoming, dated by the Carnegie group (Department of Terrestrial Magnetism, 1954–1955) by the Rb-Sr method gave an age of about 3 billion years and suggests that this area may be one of the oldest in North America. It was therefore of great interest to examine the A^{40}/K^{40} ratio in the feldspar from the Wind River Canyon nearby. The Huron Claim sample came from a hand specimen which yielded large euxenite crystals. The result which is much lower than the probable age of about 2.5 billion years may indicate that the retentivity of plagioclase feldspars is even lower than that of potassium feldspars.

The Black Hills, South Dakota, lepidolite appears to have less than 100 per cent retentivity since the most likely age for this locality is about 1620 m.y. (Eckelmann and Kulp, in press). The Brown Derby Mine result is worthy of special note since the age of 1360 m.y. for the lepidolite calculated with the 0.123 branching ratio is in good agreement with a tentative age of about 1400 m.y. suggested on the basis of extensive work in the area by Aldrich, Davis, et al., 1956. The value of about 1700 m.y. as determined by the Rb-Sr method at DTM is 1360 if multiplied by a factor of 0.8 which has been suggested as a reasonable correction for the assumed half life (Wetherill, Aldrich, et al., 1956). If the true age is about 1400 m.y. this sample argues for use of a branching ratio of about 0.12.

The Combermere, Ontario, sample alone is of

nominal interest but when considered with the other samples from the Wilberforce area, it contributes to the evaluation of the retentivity.

tions in the ages determined for a given locality beyond 5 per cent reflect differences in the sample.

TABLE 4.—A^{40}/K^{40} RATIOS FROM DIFFERENT LABORATORIES

Locality	Mineral	Laboratories	A^{40}/K^{40}
	A. IDENTICAL POWDER		
Dickinson Co., Mich.	microcline	Chicago††	(.0995)
	microcline	Lamont	.0936
	B. DIFFERENT HAND SPECIMENS		
Wilberforce, Ont.	antiperthite	Carnegie*	.0614
Fission Mine	antiperthite	Lamont	.0559
		Chicago†	.0587
Black Hills, S. D.	lepidolite	Carnegie*	.118
Ingersoll Pegmatite	lepidolite	Lamont	.117, .120
	microcline	Carnegie*	.0862
	microcline	Lamont	.0755
Spruce Pine, N. C.	microcline	Lamont	.0148
McKinney Mine	microcline	Toronto**	(.0162)

* Wetherill *et al.* (1955).

† Wasserburg (Paper presented to Am. Geophys. Union, May, 1954).

** Shillibeer, H., (Personal communication) A^{40}/K^{40} calculated.

†† Calculated for B.R. .085 and $\lambda = .551$ for purposes of comparison. $\times 10^{-9}$ yr.$^{-1}$

Interlaboratory Calibration

Table 4 gives the results from the various laboratories on samples from certain localities. Unfortunately in only the Dickinson County, Michigan, microcline was the identical powder used. This sample has been prepared and distributed by G. J. Wasserburg for intercalibration purposes to the laboratories engaged in potassium-argon work. The agreement was reasonably good for this sample. As indicated in Table 3 the Lamont value is based on a single run. In the other cases different hand specimens were employed. As far as they go these results suggest that the different laboratories, using quite different techniques, obtain similar results. The Lamont-Chicago comparison on the Dickinson County sample is particularly interesting since the Chicago group used an NaOH flux method as compared to the direct fusion technique employed at Lamont. It is concluded that all the argon is being released from the samples either with or without a flux and varia-

Problem of Retentivity

Table 5 compiles the A^{40}/K^{40} ratios for localities for which reasonably accurate uranium–lead dates are available, or where feldspar-mica comparisons can be made.

In nearly every case the feldspar retentivity is lower than that of the corresponding mica. This relationship is independent of the technique used and the laboratory which did the work. Although somewhat surprising from a structural point of view, the result might have been predicted from work done on the uranium-helium method of age determination (Keevil 1941; Hurley and Goodman, 1941). The figures in Table 5 indicate that argon retentivity is higher than helium retentivity. This is to be expected on at least two counts, (1) K^{40} decay is relatively gentle compared to uranium, and (2) the argon atom is larger than the helium atom. From a theoretical point of view, argon should not escape from a perfect crystal (Keevil, 1940). There is a pressing need for detailed studies of various factors such as exsolution,

TABLE 5.—RETENTIVITY DATA
Branching Ratio = 0.123; $\lambda_\beta = 0.476 \times 10^{-9}$ yr. $^{-1}$

Locality	Laboratory*	Mineral	A^{40}/K^{40}	Apparent per cent retentivity
Spruce Pine Dist. (Assumed age 350 m.y.)				
Hoot Owl Mine	Lamont	F	.0175	78
		M	.0213	95
McKinney Mine		F	.0148	66
		M	.0218	97
	Toronto	F	(.0162)calc.	72
Minpro	Lamont	F	.0156	69
		M	.0218	97
Mars Hill		F	.0185	83
Bryson City Dist. (Assumed age 550 m.y.)				
Deep Creek	Lamont	F	.0186	50
		M	.0378	100
S. Eastern Ontario (Assumed age 1040 m.y.)				
Wilberforce	Lamont	F	.0559	69
	Chicago	F	.0587	72
	Carnegie	F	.0614	75
		M	.0695	85
Blackstone Lake Pit				
Congers Twp.	Chicago	F (2)	.0556	68
		F (2)	.0543	67
		M	.0706	87
		F (3)	.0456	56
		F (4)	.0592	73
	Toronto	F	.0557	68
		M	.065	80
Cardiff Twp.	Chicago	F (5)	.0629	77
		F (6)	.0587	72
Tory Hill		F (7)	.0540	66
		granite	.0542	67
Dill Twp.	Toronto	F	.052	64
		M	.049	60
Combermere	Lamont	F	.0450	55
Black Hills, S. D. (Assumed age 1630 m.y.)				
	Lamont	F	.0755	50
		M	.118	78
	Carnegie	F	.0862	57
		M (lepidolite)	.118	78
		M (muscovite)	.137	90

* For references to work from other laboratories see Table 4.

alteration, lineage cracks, fractures, which may allow argon loss. A preliminary examination of thin sections of samples run in this laboratory does not indicate any single factor as being responsible. The quantity of string perthite, however, and the extent of fracturing appear to vary in the right direction in most of the Spruce Pine feldspar samples.

The feldspar retentivity for the southeast Ontario samples based on an age of 1040 m.y.

and using the stated constants varies from 55 to 77 per cent. It would seem clear that there is no single value of the branching ratio which will bring the feldspar ages into line. According to Wasserburg, Chicago samples 2, 3, and 4 were from the same pegmatite complex and 2 and 3 were from the same pegmatite. Samples 5 and 6 were also from a single pegmatite (Wasserburg and Hayden, 1955).

The retentivity of the feldspars appears to decrease in a general way. Wetherill, Wasserburg, *et al.* (1956) report micas 1.9 and 2.6 b.y. old which retain essentially all their argon. If the factors causing argon loss are the same as those affecting helium then it appears reasonable that other minerals such as hornblende may have high retentivity. Increased mass spectrometer sensitivity will make it possible to extend the method to include studies of certain low K content minerals which may also have higher retentivity. Therefore, any correction factor applied to compensate for argon loss will depend to a small extent on the age of the sample. The average retentivity for the Spruce Pine feldspars is about 76 per cent; for the 1040 m.y.-old Wilberforce area, about 68 per cent; and for the 1500-areas about 50 per cent. Undoubtedly several factors contribute to this relation. The most important are crystal structure and metamorphic history. The value of the Deep Creek feldspar may be related to the later regional thermal rise which produced the Spruce Pine pegmatites but which did not cause recrystallization in the Bryson City district.

It is important in any application of potassium-argon ages or in retentivity studies to take into account the effect of metamorphism. Calibration work must be done in areas where there has been no metamorphism subsequent to mineral formation or where the thermal history is fairly well understood. It is expected that when properly understood the loss of argon in varying amounts from different minerals will provide valuable clues to the metamorphic history of an area.

Discussion

General Statement

In order to judge the validity of ages derived from potassium-argon measurements it is necessary to analyze samples from localities which have been dated by other quantitative methods. Since this condition is difficult to meet, measurements have been made on specific pegmatites whose ages are quite well established by self-consistent uranium-lead ages. Various minerals from the same well-dated pegmatites have been compared. Finally, to establish the general application of the method regional studies were made in areas where a knowledge of the geology permits a critical test. These comparisons permit evaluation of both the branching ratio and the retentivity problems.

Table 6.—Southern Appalachian Potassium-Argon Ages
B.R. = 0.123; $\lambda_\beta = 0.476 \times 10^{-9}$ yr.$^{-1}$

	Apparent Age (m.y.)	
	Feldspar	Mica
Pegmatite Mines		
Hoot Owl Spruce Pine Dist., N.C.	276	332
McKinney Spruce Pine Dist., N.C.	236	338
Minpro Spruce Pine Dist., N.C.	248	338
Mars Hill Spruce Pine Dist., N.C.	292	
Deep Creek, Bryson City Dist., N.C.	292	543
Host Rocks		
Cranberry gneiss (1)	402	
(2)	378	
Carolina gneiss (1)	378	
(2)	368	
Henderson gneiss	260	
Beech granite	403	

The Spruce Pine District of western North Carolina contains a swarm of commercial pegmatites containing a considerable variety of radioactive minerals. A number of specimens of samarskite and uraninite from different pegmatites have been analyzed isotopically giving the various uranium-lead and thorium-lead ratios. The best age derived from these samples is 350 ± 20 m.y. (Eckelmann and Kulp, in press). Note (Table 6) that fresh muscovite samples from three of these pegmatites give 332, 338, and 338 m.y. (error on each probably ±15) in good agreement if a branching ratio of 0.123 and $\lambda_\beta = 0.476 \times 10^{-9}$yr.$^{-1}$ is used. If Suttle and Libby's value of 29.6 betas/sec/gm K or $\lambda_\beta = 0.508 \times 10^{-9}$yr.$^{-1}$ is

used with a branching ratio of .115 the resulting mica age for these samples is about the same. Such a branching ratio requires a gamma decay constant of 3.4 γ's/sec/gm K which is the average of the best physical data. Thus it appears that within the experimental uncertainties the geological and physical branching ratios agree for this locality and that the true branching ratio cannot reasonably be lower than .110. This locality is particularly desirable since the formation of the pegmatites represents the last detectable metamorphic event in the region so that there is little likelihood of subsequent alteration.

TABLE 7.—POTASSIUM-ARGON AGES FOR BEAR MOUNTAIN, N. Y.
B.R. = .123; $\lambda_\beta = .476 \times 10^{-9}$ yr.$^{-1}$

	Minimum Age (m.y.)*	Probable Age† (m.y.)
Storm King granite (negligible mica)	537	~800
Storm King pegmatite	535	~800
Canada Hill gneiss	1110	~1400
Pegmatite within Canada Hill phase	654	~900

* These ages are uncorrected for possible argon loss.

† Assumed retentivity 60 per cent for feldspar, 90 per cent for mica.

Bear Mountain, New York, Area

The results on samples from the Bear Mountain, New York area are given in Table 7. The detailed geological implications have been discussed elsewhere (Carr, Lowe, and Kulp manuscript). This provides an example of the usefulness of the K-A method even with its present problems. The data suggest that the Storm King granite is younger than the Canada Hill gneiss as had been proposed by Lowe on a detailed petrologic and structural study. They show that the Storm King granite is Precambrian not Paleozoic as some geologists had suggested and that the New Jersey-New York Highlands complex is more than 1 b.y. old, and thus considerably older than the Blue Ridge Province of the Southern Appalachians. The pegmatite feldspar in the Canada Hill gneiss is either of Storm King age or has much lower retentivity than the other feldspars examined.

Southern Appalachian Geology

The metamorphic complex in the Blue Ridge Province of North Carolina was selected for the first brief regional survey. Detailed geologic mapping has been done in several portions of the region. Kulp and Brobst (1956) completed a map of about 300 square miles in the Spruce Pine District in an effort to understand the origin of pegmatites and their relation to the regional geology. King, Hadley and others of the U. S. Geological Survey have been working in the Great Smoky Mt. Park area southwest of Asheville. Fresh samples are available from pegmatites which are being worked at present in the Spruce Pine, Bryson City, and Franklin-Sylva areas. Potassium-argon ages on feldspars and micas from some of these pegmatites afford an opportunity to judge the consistency of results for pegmatite minerals. These may be compared with the ages obtained on samples of the host rocks of the area.

The ages obtained for the feldspars and micas of a number of North Carolina pegmatites are shown in Table 6. As discussed above the feldapar ages are low due to loss of 15–35 per cent of the argon, whereas the micas give essentially the correct ages.

The mica ages confirm the U-Pb age results and suggest that the last regional metamorphism in the Spruce Pine District which produced these pegmatites occurred about 350 m.y. ago.

Table 6 also gives the ages for some of the host rocks of the area run as such without any mineral separation. These results must be understood to represent minimum ages. Complete descriptions of the rocks are given by Parker (1953), Kulp and Brobst (1956), and F. D. Eckelmann and Kulp (1956). It has been postulated that the Cranberry gneiss which is a light-colored gneiss containing mainly quartz and feldspar and a little biotite and muscovite, is of sedimentary origin and was metamorphosed in the Precambrian. The Beech granite is of similar composition and intrudes the Cranberry. The Carolina gneiss overlies the Cranberry and is also thought to be part of the original Precambrian sedimentary sequence. It is a mica gneiss containing quartz and pla-

gioclase feldspar. The Henderson gneiss is stratigraphically equivalent to the Cranberry and is similar in composition.

The apparent ages of the host rocks with the exceptio n of the Henderson gneiss are older than that given by the mica in the Spruce Pine pegmatites. Since these gneisses are made up largely of feldspar, and probably were subjected to a later thermal rise accompanying the Spruce Pine pegmatite invasion, the average retentivity probably does not exceed 60 per cent. The good agreement between the Beech, Cranberry, and Carolina indicates that they were formed at approximately the same time in the Precambrian in accordance with previous geologic interpretation. The most probable age of these rocks and hence the primary regional metamorphism based on a retentivity of 60 per cent for the feldspar is 630 ± 100. Thus although the error is largely due to the uncertainty in the retentivity, all these rocks appear to have the same age and are late Precambrian. The Henderson gneiss sample is very fine-grained and slightly weathered, hence it might be expected to have lower retentivity. Without further experiments it cannot be said to differ in age from the Cranberry.

At least two metamorphic periods are probably necessary to account for the ages determined for the pegmatites and host rocks. The first period would be that in which the original sedimentary sequence was metamorphosed to give the Cranberry and Carolina gneisses. The Beech granite originated at the same time possibly by fusion of some of the lower Cranberry followed by intrusion. This first metamorphic period would have occurred between 550 and 750 m.y. ago.

The second period of metamorphism was that which caused the emplacement of the pegmatites about 350 m.y. ago. This agrees with geologic evidence of the thermal metamorphism of the Bakersville basalt rocks which were intruded into the Carolina gneiss after its plastic deformation but before the intrusion of the Triassic diabases (Kulp and Poldervaart, 1956).

The Deep Creek pegmatite minerals contribute to this picture. The Deep Creek No. 1 Mine is located in Bryson City in the southwest corner of North Carolina. It has been described in detail by Cameron *et al.* (1949). Two periods of metamorphism have been postulated for this area also. The mica age of about 550 m.y. would set a lower limit to the first period of metamorphism and the date of emplacement of the pegmatites. The feldspar age of 292 m.y. falls in line with feldspar ages of the Spruce Pine district and points to a loss of the major portion of the argon from the Deep Creek feldspar at the same time that the second period of regional metamorphism was causing the emplacement of pegmatites near Spruce Pine.

It is desirable to do additional work in this area. Further studies of different minerals taken from various zones of a single pegmatite and the immediately surrounding country rock should be made. The Rb-Sr method which is least susceptible to thermal effects should be employed to examine the micas of these pegmatites. The broad history of the Southern Appalachians is developing, but much detail must be supplied. The metamorphic complex (the "Archean" of Keith, 1903) is in reality quite young but apparently precedes the Cambrian.

Conclusions

(1) It has been demonstrated by tracer techniques, calibration samples, and reproducibility of results that the argon content of a rock can be released and measured with an accuracy of about ±3 per cent.

(2) Potassium analyses can be made with an accuracy of at least ±3 per cent in most cases.

(3) The branching ratios as measured by geologic and physical methods are in essential agreement at a value of about 0.12.

(4) Most of the geologic measurements pointing to a low branching ratio can be explained on the basis of incomplete retention of argon within the sample. This difficulty does not render the whole method invalid since there are minerals such as micas which retain from 80 to 100 per cent of their argon. In most cases feldspars retain less of the argon than micas and in the case of feldspar the per cent loss may increase with age.

(5) All the rocks of the Bear Mountain area are Precambrian; the Stone King granite was intruded about 800 m.y. ago, and the Canada Hill granite gneiss was formed somewhat earlier.

(6) The application of the potassium-argon method in the Southern Appalachians points to

two periods of metamorphism; the first about 550–750 m.y. ago and the second about 350 m.y. ago. The Spruce Pine District Pegmatites are related to the second period of metamorphism.

(7) Studies must be made to determine the factors affecting argon retention in a mineral and methods of evaluating these factors. While awaiting the results of such studies, many problems of geological interpretation can be resolved if a careful selection of samples is made to allow the qualitative evaluation of the extent of argon loss.

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Lamont Geological Observatory, Columbia University, Palisades, N. Y.
Manuscript Received by the Secretary of the Society, May 21, 1956
Lamont Contribution No. 212

Short Notes

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 68, PP. 785-790, 2 FIGS., 1 PL. JUNE 1957

APPLICATION OF PRINCIPLES OF WRENCH-FAULT TECTONICS OF MOODY AND HILL TO NORTHERN SOUTH AMERICA

BY H. ALBERDING

The purpose of this paper is twofold: (1) to point out the ideal way in which the principles of wrench-fault tectonics expressed by Moody and Hill (1956, p. 1207–1246) apply to northern South America (northern Venezuela, Trinidad, and northeastern Colombia); and (2) to present evidence which suggests movements of land masses along the strike-slip (wrench) faults along the southern edge of the Caribbean in northern South America comparable and complementary to those movements which occurred, according to Hess and Maxwell (1953, Fig. 2, p. 4), along strike-slip (wrench) faults in the Greater Antilles and Central America in the northern part of the Caribbean.

Figures 1 and 2 and Plate 1 have been prepared to illustrate these ideas. Plate 1 presents such basic data as: (1) rock types on either side of the major strike-slip (wrench) faults in northern Venezuela and Trinidad that illustrate horizontal displacements; (2) respective ages of the principal strike-slip (wrench) faults; and (3) the pattern of thrust and normal faults in relation to the wrench faults. Plate 1 is essentially based on Bucher's (1950) Geologic-tectonic map of the United States of Venezuela, with numerous modifications and additions from more recently published maps and the writer's observations. Thus, the principal strike-slip (wrench) faults of Rod (1956, p. 457–476) have been added to Bucher's map with modifications made, in turn, of Rod's faults based in part on data presented by O. Renz (1956, Fig. 3). Rod's (1956, Fig. 2, p. 459) Ocoa (Oca) strike-slip fault is modified by Renz's Paez fault zone, and Rod's (1956, Fig. 6, p. 464) Bocono fault is modified by Renz's (1956, Fig. 3) Santo Domingo-Barquisimeto fault. Also, the writer projects Rod's (1956, Fig. 9, p. 469) El Pilar fault westward to extend along the northern coast of the Cordillera de la Costa in the Caracas region of northern Venezuela. The writer does not accept the interpretation that numerous subsidiary strike-slip faults turn into thrusts (Rod, 1956, Fig. 1, p. 458). The extension of the El Pilar fault along the south base of the Northern Range of Trinidad follows Rod's (1956, Fig. 9, p. 469) interpretation, and the San Francisco and Tigre strike-slip (wrench) faults also follow Rod's (1956, Fig. 9, p. 469; Fig. 2, p. 459) mapping. The faults on the Guajira Peninsula are taken from Raasveldt (1956, Fig. 2, p. 21), and a selected few of the subsurface faults in and next to Lake Maracaibo follow mapping by the Staff of Caribbean Petroleum Company (1948, Fig. 3). Most of the faults in eastern Venezuela are from a map of that region prepared by the writer (H. H. Renz, *et al*, in print, Fig. 12).

On the basis of data mostly from Bucher's (1950) geologic-tectonic map, two rock types are shown on Plate 1: Paleozoic and Precambrian rocks and Cretaceous metamorphic and igneous rocks. These two types illustrate the horizontal displacements along the major strike-slip faults in northern Venezuela and Trinidad. Thus, the suggestion is that the Cretaceous metamorphic rocks and igneous rocks of the Araya and Paria peninsulas, the Northern Range of Trinidad, and the islands of Margarita and Tobago originally (during the Cretaceous) all lay 475 km to the west, opposite the Cretaceous metamorphic rocks and igneous rocks of the Cordillera de la Costa of the Caracas region, prior to strike-slip (wrench) faulting along the El Pilar fault. The marked similarity in thicknesses and types of Cretaceous rocks in the Northern Range of Trinidad and in the Los Teques-Cua region of the Caracas area gives credence to this idea. Kugler (1953, p. 33)

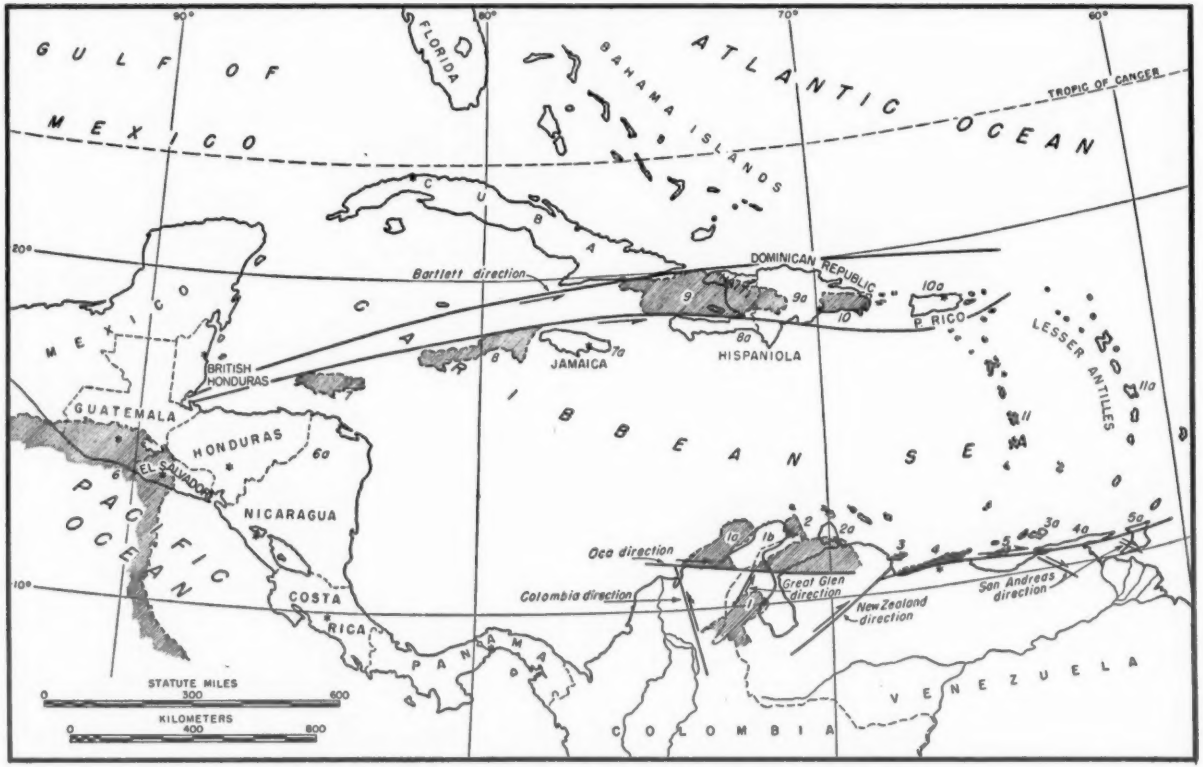

FIGURE 1.—PRINCIPAL STRIKE-SLIP (WRENCH) FAULTS OF CARIBBEAN AREA

Showing displacements of land masses (shaded areas represent positions prior to faulting). Greater Antilles and Central America after Hess and Maxwell. Wrench-fault directions after Moody and Hill.

pointed out a possible relationship between the San (Sans) Souci volcanic rocks of the Northern Range of Trinidad, which consist of a series of

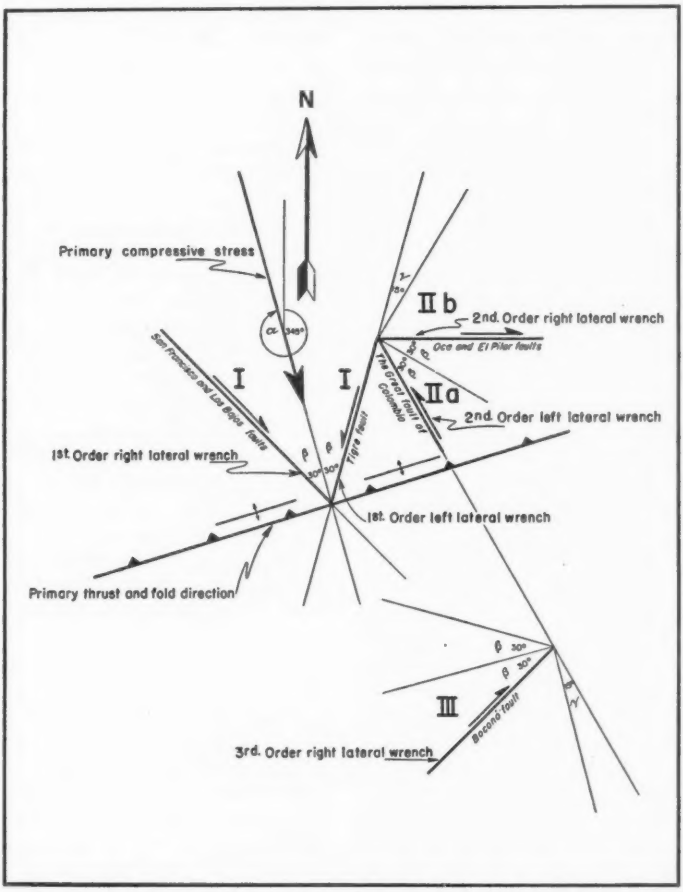

FIGURE 2.—PLAN OF WRENCH-FAULT SYSTEM DEVELOPED IN NORTHERN SOUTH AMERICA
With α of primary compressive stress = 345° (after principles of Moody and Hill).

consolidated volcanic tuffs, tuff breccias, agglomerates, and lava flows of an andesitic composition, and the Tiara volcanic rocks of the Los Teques-Cua region which Smith (1953, p. 58–59) describes as basaltic extrusives and associated volcanic agglomerate, tuff, and graywacke intruded by gabbro sills and dikes. Furthermore, the thickness of perhaps 10,100 m (33,128 feet) of the Cretaceous part of the Caribbean series in the Northern Range of Trinidad (Kugler, 1953, p. 33) is much closer to the 7950 m (26,076 feet) of Cretaceous rocks reported by Smith (1953, p. 46–58) from the Los Teques-Cua region of the Caracas area, than to the possible 2100 m (6888 feet) of Cretaceous sediments reported by Kugler (1953, p. 36–38) from central and south Trinidad and the 3177 m (10,420 feet) of Cretaceous reported by Hedberg (1950, p. 1185-1195) from the Rio Querecual area south of the El Pilar fault in northeastern Venezuela. In other words, known thicknesses of Cretaceous sediments north of the El Pilar fault in northeastern Venezuela and Trinidad are markedly dissimilar to thicknesses of Cretaceous sediments south of the fault in this region

and more closely similar to Cretaceous thicknesses south of the fault in the Caracas region. This similarity likewise applies to the degree and extent of metamorphism of Cretaceous sediments north and south of the El Pilar fault. The metamorphism in the Araya and Paria peninsulas, the Northern Range of Trinidad, and the islands of Trinidad and Margarita are similar to the metamorphism in the Caracas region, whereas most of the Cretaceous sediments south of the El Pilar fault in northeastern Venezuela and Trinidad are unmetamorphosed. (However, *see* Rod, 1956, p. 470–472, who points out that the El Pilar fault does not separate Cretaceous metamorphic rocks from nonmetamorphic rocks as sharply as shown on Bucher's tectonic map).

Strike-slip (wrench) displacements along the Bocono fault are also suggested by the distribution of the two rock types shown on Plate 1. Thus, Cretaceous metamorphic rocks and igneous rocks appear to have been displaced along the Bocono fault as much as 45 km in southeastern Lara, and there is a strong suggestion that the Venezuelan Andes are split lengthwise by the Bocono fault and its southwestern extensions which have strike-slip displacements up to 65 km as shown by the distribution of Paleozoic and Precambrian rocks in Trujillo, Merida, and Tachira. Rod's (1956, p. 463–468) treatment of the Bocono fault, which he named, is admirable except for the part of the fault southwest of the city of Merida which Rod (1956, Fig. 6, p. 464) shows as much too simple compared with the more detailed map of O. Renz (1956, Fig. 3).

Strike-slip movements along the Tigre fault are perhaps as much as 35 km as shown by the distribution of Paleozoic and Precambrian rocks on either side of the fault, and on the Guajira Peninsula there are strike-slip (wrench) displacements up to 15 km based on the data of Raasveldt (1956, Fig. 2, p. 21).

Figure 1 presents the writer's conception of movements of land masses along strike-slip (wrench) faults in northern South America combined with the displacements which took place in the Greater Antilles and Central America (Hess and Maxwell, 1953, Fig. 2, p. 4). The nomenclature of the fault directions is the terminology used by Moody and Hill (1956, Fig. 20, p. 1234). Shaded areas represent the positions of land masses prior to strike-slip (wrench) faulting which is assumed to have begun toward the end of the Cretaceous.

The strike-slip (wrench) movement of the Guajira Peninsula from position 1 to 1a (Fig. 1) is based on data presented by Raasveldt (1956, Fig. 5, p. 25) who shows a left-lateral wrench displacement along the Great Fault of Colombia (the Colombia direction of Fig. 1) of 240 km assuming that the Santa Marta massif was originally opposite the Colombian Cordillera Central. Following this movement the Guajira Peninsula was moved eastward more than 100 km, from position 1a to 1b, along the Oca right-lateral strike-slip (wrench) fault. The close similarity of the rocks in the Guajira Peninsula with those in the Santa Marta massif and these, in turn, with the rocks of the Cordillera Central makes the assumption of all these strike-slip movements reasonable (Mapa geologico general de la Republica de Colombia, 1944). The right-lateral movement of the Guajira Peninsula along the Oca fault must have affected all rocks north of the fault, and the Paraguana Peninsula (Pl. 1) is consequently shown as having moved from position 2 to 2a on Figure 1. Strike-slip displacements along the El Pilar fault are shown by movement of Margarita Island from position 3 to 3a; the Araya and Paria peninsulas from position 4 opposite Caracas to their present position at 4a; and the Northern Range of Trinidad from position 5 to 5a. Evidence of these movements has been presented above.

Strike-slip displacements in the northern part of the Caribbean and Central America, according to Hess and Maxwell (1953, Fig. 2, p. 4), is based on analysis of local tectonics and on their assumption that Cretaceous metamorphic rocks which are now separated were originally in juxtaposition. They show that part of Central America moved from position 6 to 6a (Fig. 1); Jamaica from position 7 to 7a; southern Hispaniola from position 8 to 8a; northern Hispaniola from 9 to 9a; and Puerto Rico from 10 to 10a. That there are major faults in this region along which strike-slip movements could have taken place is shown on any good bathymetric chart of the northern Caribbean (Woodring, 1954, Pl. 1; National Geographic map of West Indies, 1954). The Lesser Antilles are shown as having moved 400 km from position 11 to 11a, although it should be remembered that the Lesser Antilles

as they exist today are perhaps the result, in part, of a crumpling along the front of the Caribbean block as it moved eastward (Bucher, 1947, p. 110). Eugeosynclinal conditions must have persisted in at least the northern part of the Lesser Antilles (St. Bartholomew Island) until middle Eocene time as shown by middle Eocene limestones interbedded with andesitic pyroclastic rocks intruded by quartz diorite (Woodring, 1954, p. 727, who quotes Christman, 1953, p. 67–73).

Figure 2 shows a plan of the strike-slip (wrench) fault system developed in northern South America according to the principles of Moody and Hill (1956, Fig. 5, p. 1213). The primary compressive stress is assumed to have been exerted from a N. 15° W. direction (α = 345°) so that the various fault directions should be oriented correctly (Moody and Hill, Fig. 20, p. 1234). These two authors have developed the theory that, under a primary compressive stress, first-order shear planes develop at an angle (β) of 30° to the stress direction and that right- or or left-lateral wrench movements along these first-order shear planes produce second-order shear planes with right- or left-lateral wrench movements, and that these, in turn, produce third-order shear planes with right- or left-lateral wrench movements. Shear directions are duplicated in the third-order and since two of the third-order shears are repetitions of first-order shears in movement and direction and since all fourth and lower-order shears repeat previous directions and movements, eight major shear directions result (Moody and Hill, 1956, p. 1212–1213). The first-order shear movements should be the oldest and should be cut by second-order shears which, in turn, should be cut by third-order shears. Also, either right- or left-lateral movements of whatever order could be dominant and fracture before the other. Each major shear direction has been given a name chosen from prominent wrench faults all over the world (Moody and Hill, 1956, Fig. 20, p. 1234).

In northern South America, the Great Glen and San Andreas first-order shear directions (Fig. 2, I) are represented by the Tigre fault (a left-lateral Great Glen direction wrench) and the San Francisco and Los Bajos faults (right-lateral San Andreas direction wrenches). Movements along first-order left-lateral wrenches produced second-order right- and left-lateral wrenches of Colombia and Oca directions which cut the first-order faults. The Great Fault of Colombia is the type fault for the Colombia direction and is a second-order left-lateral wrench (II a) which broke before the second-order right-lateral wrenches such as the Oca and El Pilar faults (II b). The Oca fault is the type for the Oca direction and probably was connected with the El Pilar fault prior to being offset by the Bocono fault which is a third-order right-lateral wrench (III), following the New Zealand direction of Moody and Hill nomenclature.

The development of shear planes as shown by Rod (1956, Fig. 11, p. 473) is just opposite from what the writer postulates: Rod shows an east-west strike-slip movement along the El Pilar fault (a second-order right-lateral wrench) as causing the development of a first-order right-lateral wrench (the San Francisco fault of San Andreas direction of Moody and Hill nomenclature).

The primary thrust direction developed at right angles to a primary compressive stress with α = 345° is shown on Figure 2, and Plate 1 shows that the major thrust faults in northern Venezuela and Trinidad follow this direction. Primary fold directions parallel primary thrust directions, and Bucher's (1950) geologic-tectonic map of Venezuela shows this to be true in this area with S-shaped distortions of the primary folds through Trujillo, eastern Zulia, and Lara as perhaps the effects of the right-lateral movement along the Bocono fault.

In the northern Caribbean, the great faults of the Bartlett trough are the type for the Bartlett direction and represent second-order left-lateral wrenches. Other structural elements in the Greater Antilles would follow directions which are mirror images of directions in northern South America (Bucher, 1947, p. 111).

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Manuscript Received by the Secretary of the Society, January 15, 1957

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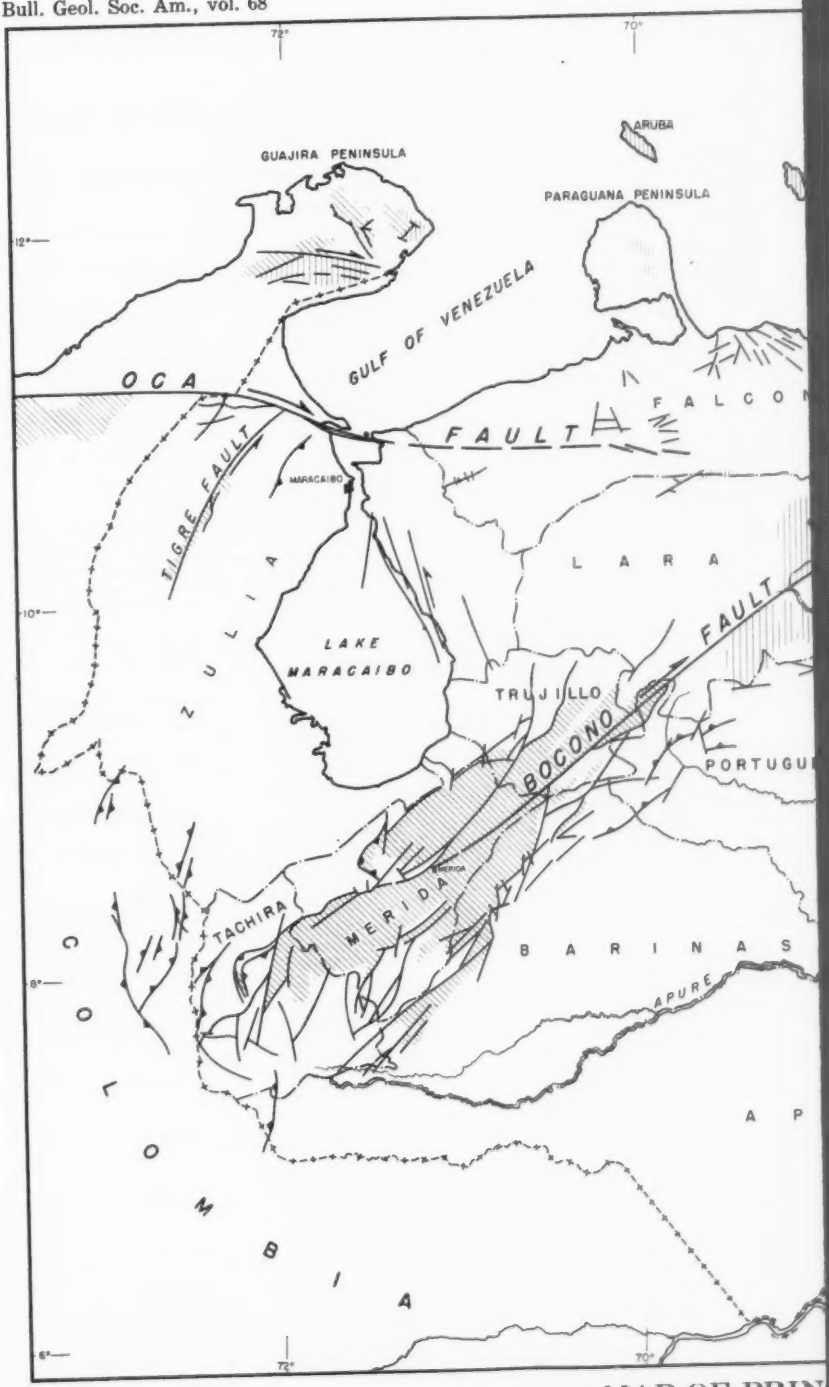

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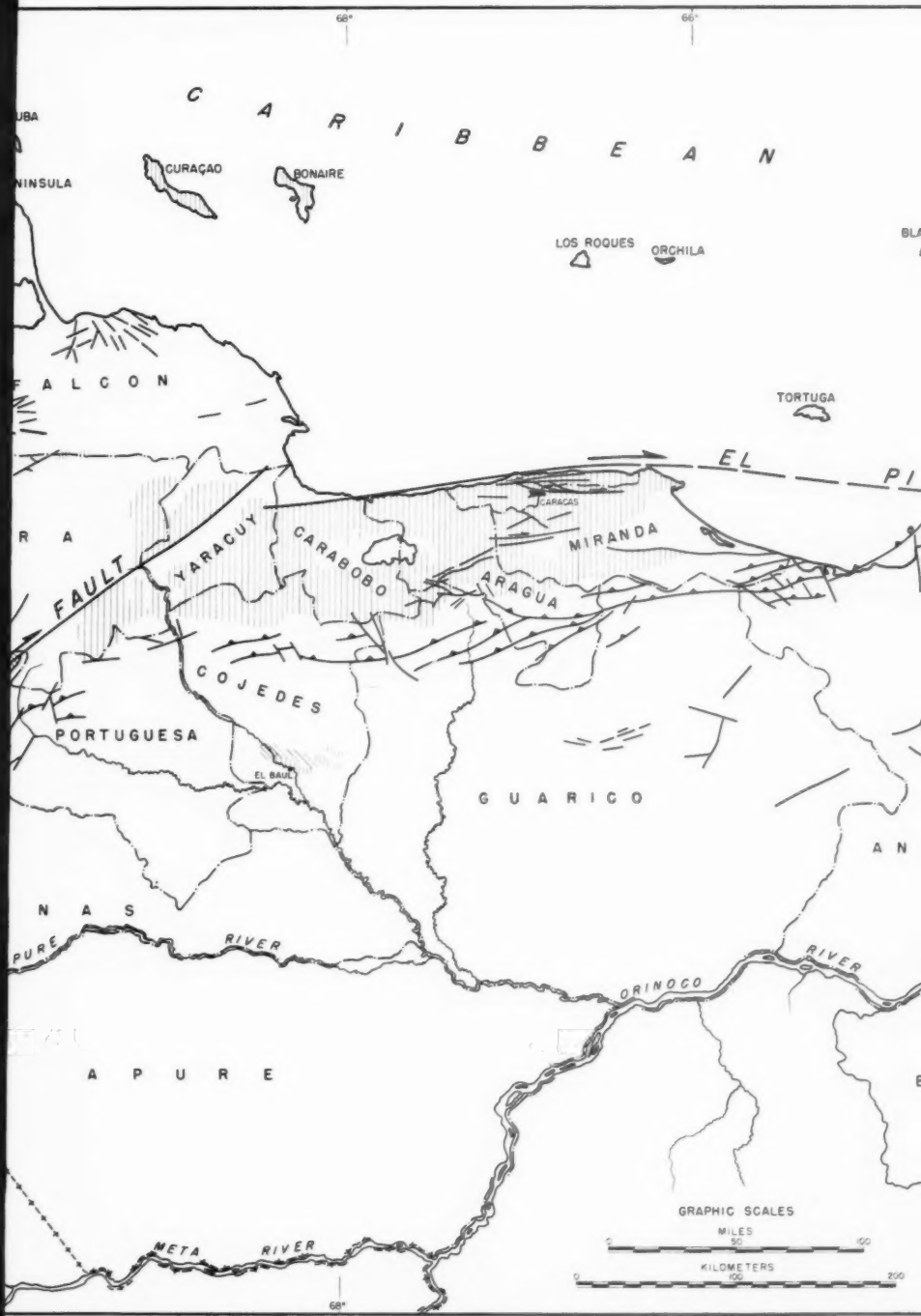

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Modified after W. H. Bucher, E. Rod, O. Renz, H. C. Raasveldt, H. H. Suter, and oth

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